



---

# Status of Ground-based Gravitational Wave Detectors

Peter R. Saulson  
Syracuse University



# Outline



- 
1. State of the art: bars
  2. State of the art: interferometers
  3. The global network
  4. Data analysis results highlights
  5. Near- to mid-term prospects



# Summary



---

Gravitational wave detectors on the ground are now operating full-time at unprecedented sensitivity.

Detection of gravitational waves by ground based detectors *is* expected, if not from this generation, then from its successors that will start construction within a few years.

# Gravitational Wave Detectors

**Allegro,  
LSU  
Louisiana**

**MiniGRAIL,  
Leiden (Olanda)**

**Auriga,  
Legnaro**



MINIGRAIL  
GEO  
EXPLORER  
AURIGA  
NAUTILUS



**Explorer,  
CERN**

MARIO SCHENBERG

**Schenberg,  
San Paolo (Bra)**

**Nautilus,  
Frascati**



AIGO  
NIOBE

## Antenne risonanti nel mondo

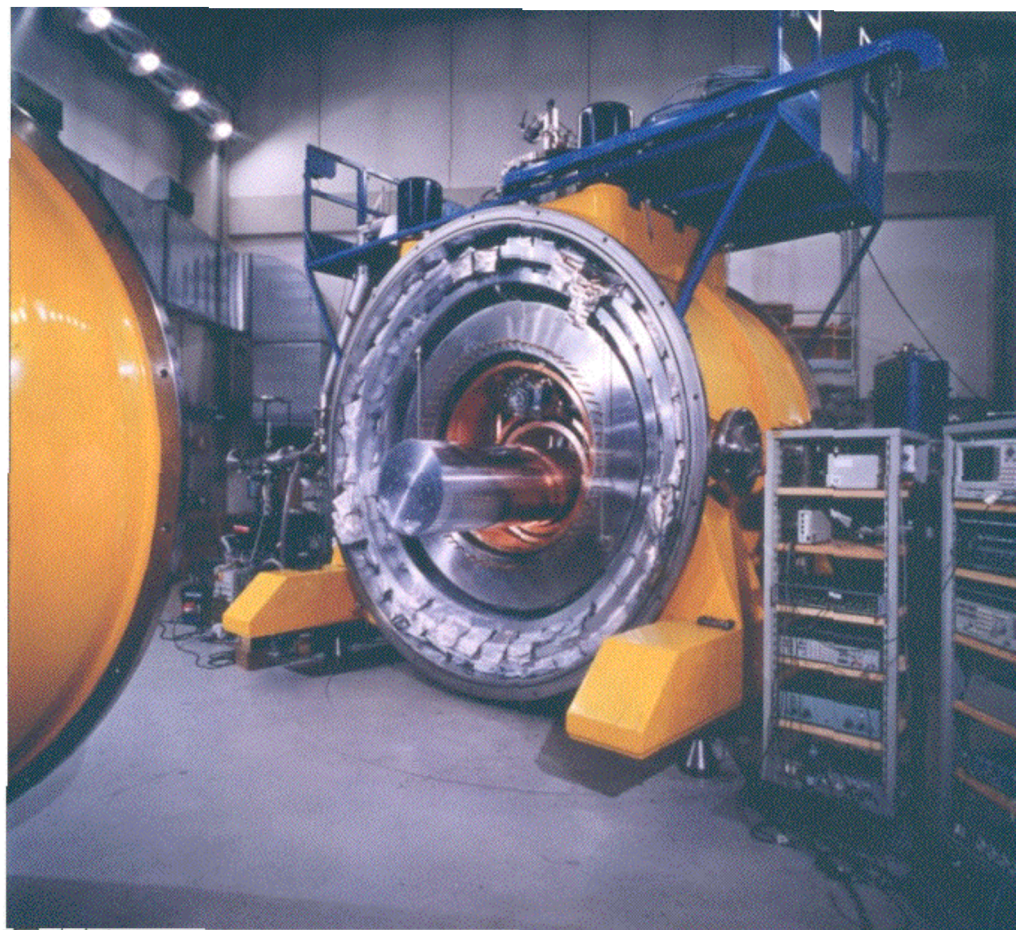
gravitational wave research

# Resonant detectors (or “bars”)

The original  
gravitational wave  
detection technology.

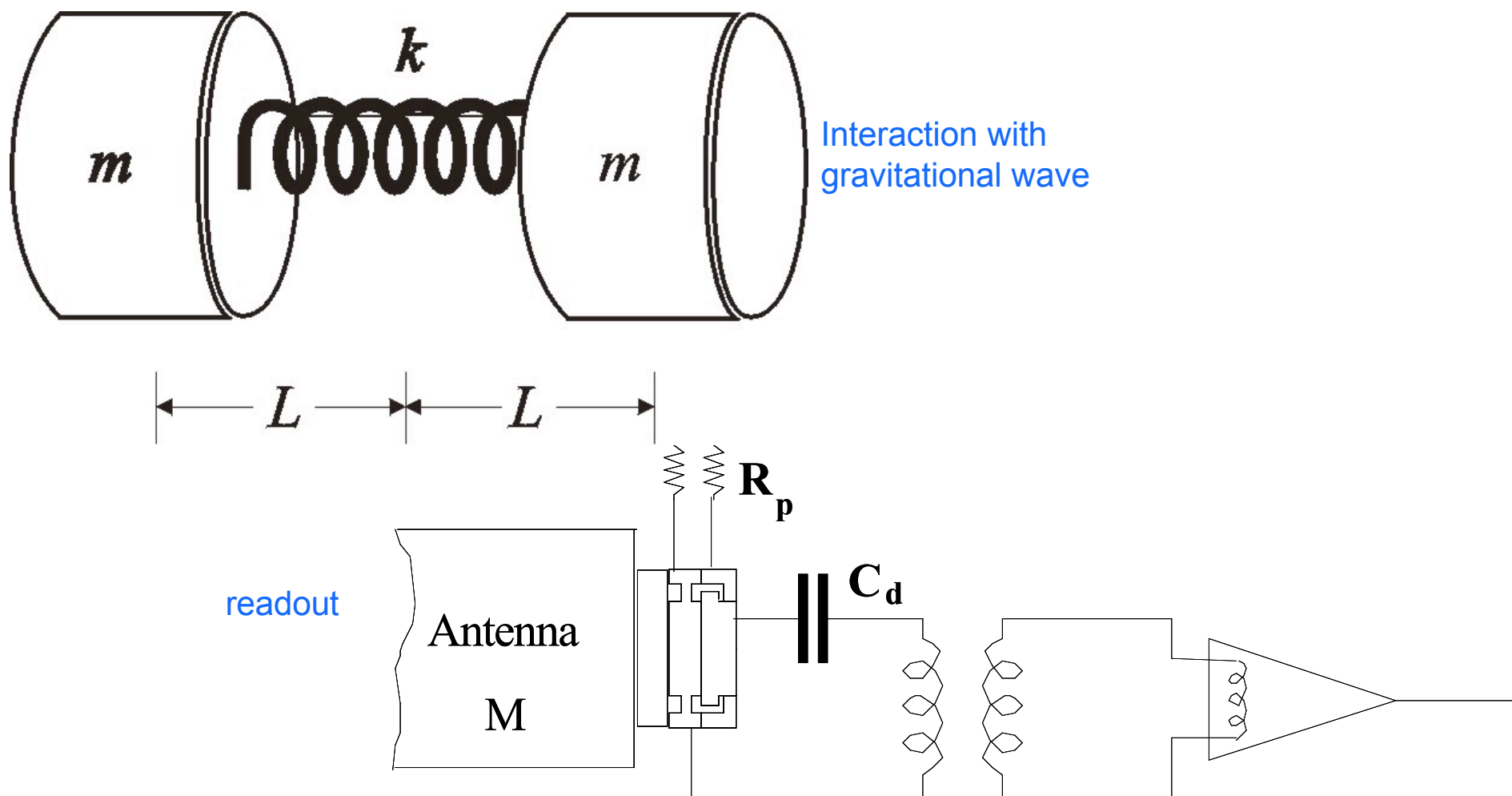
Now, operating at  
cryogenic temperatures,  
sensitivities of  $h_{rms} \sim 10^{-19}$ .

They are reliable and have  
excellent duty cycle.

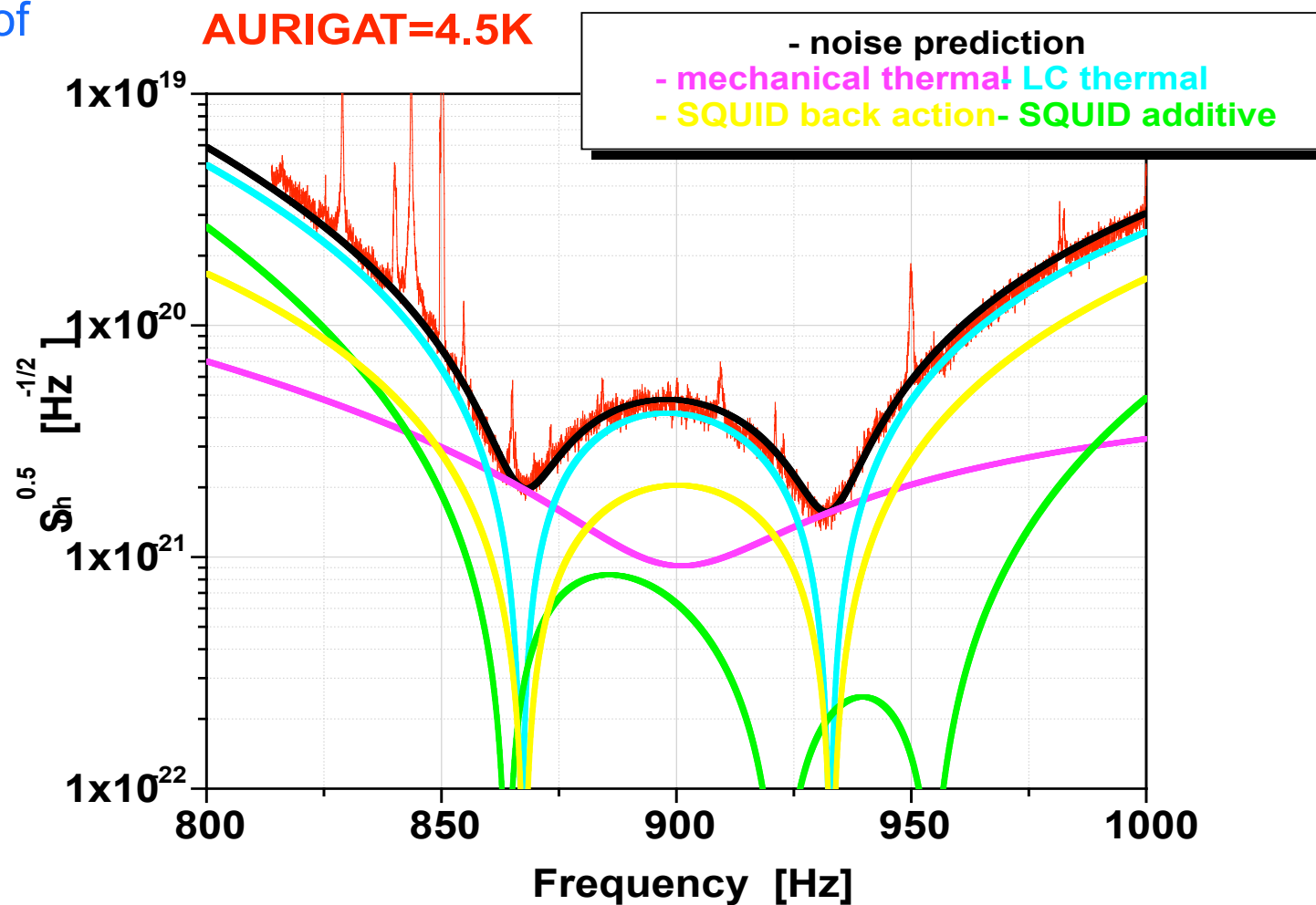


AURIGA

# Basic idea of resonant detectors

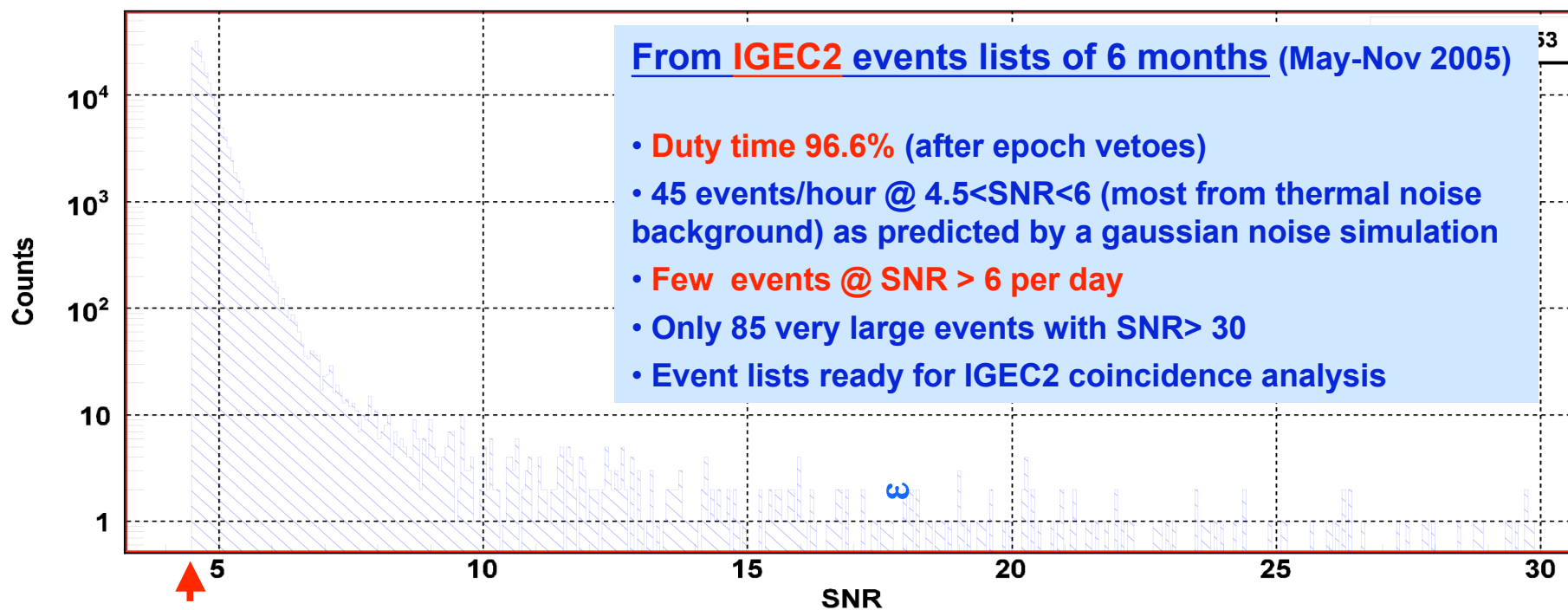


Note success of  
noise model.



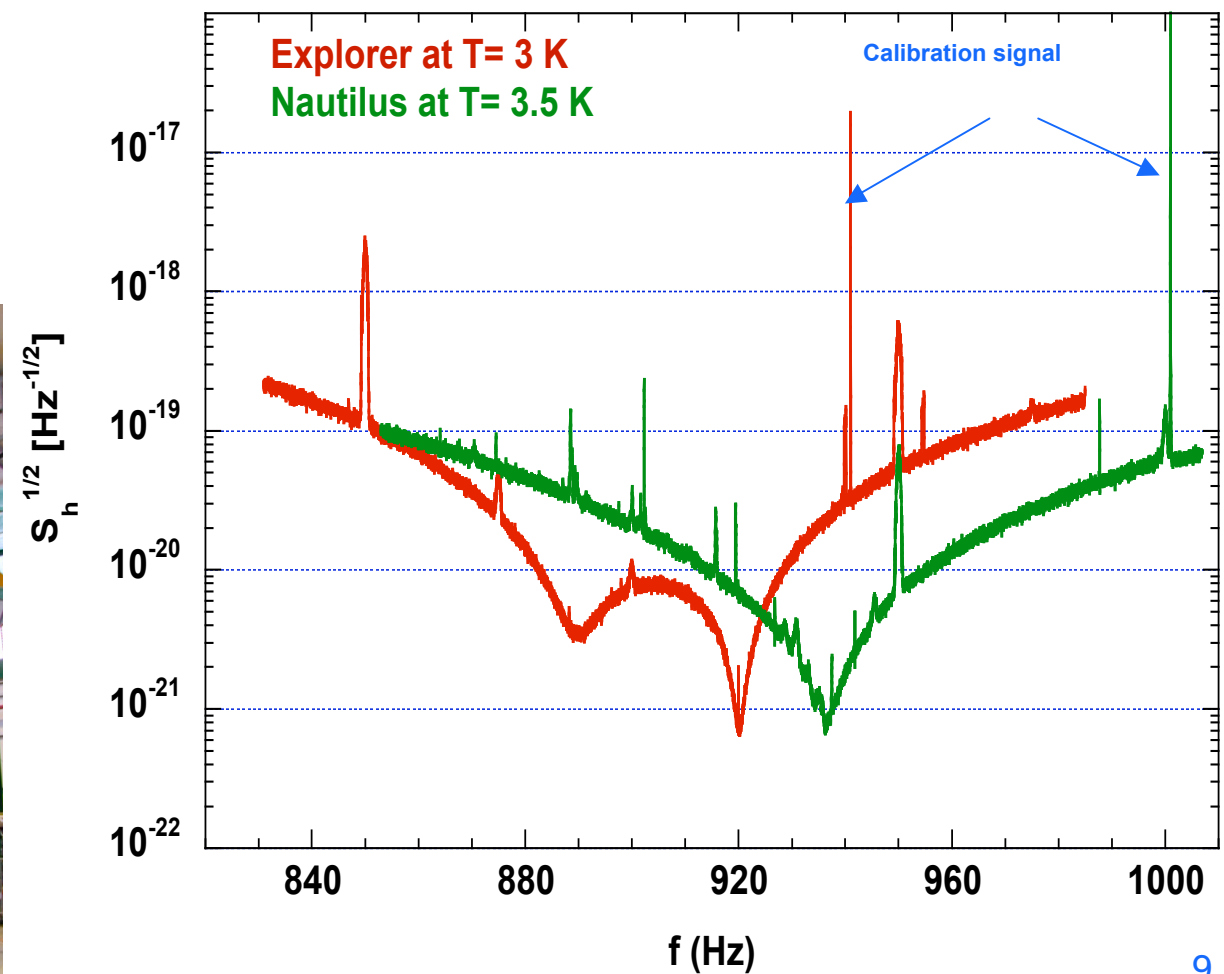
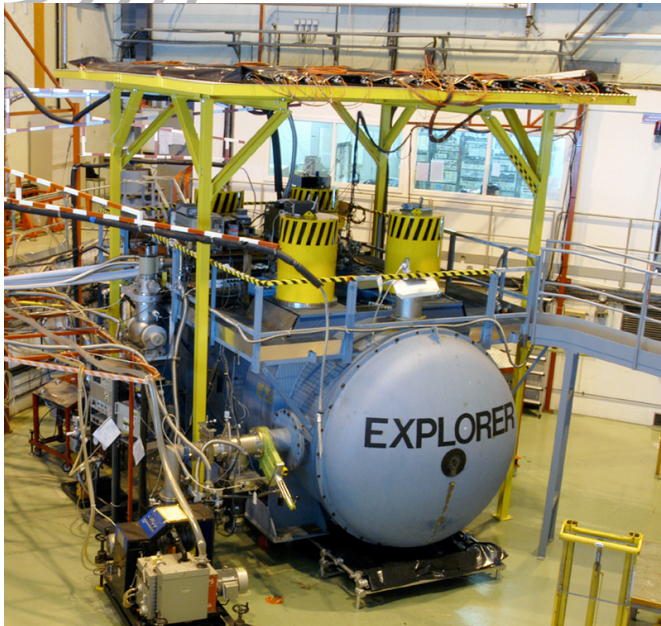


# AURIGA output histogram

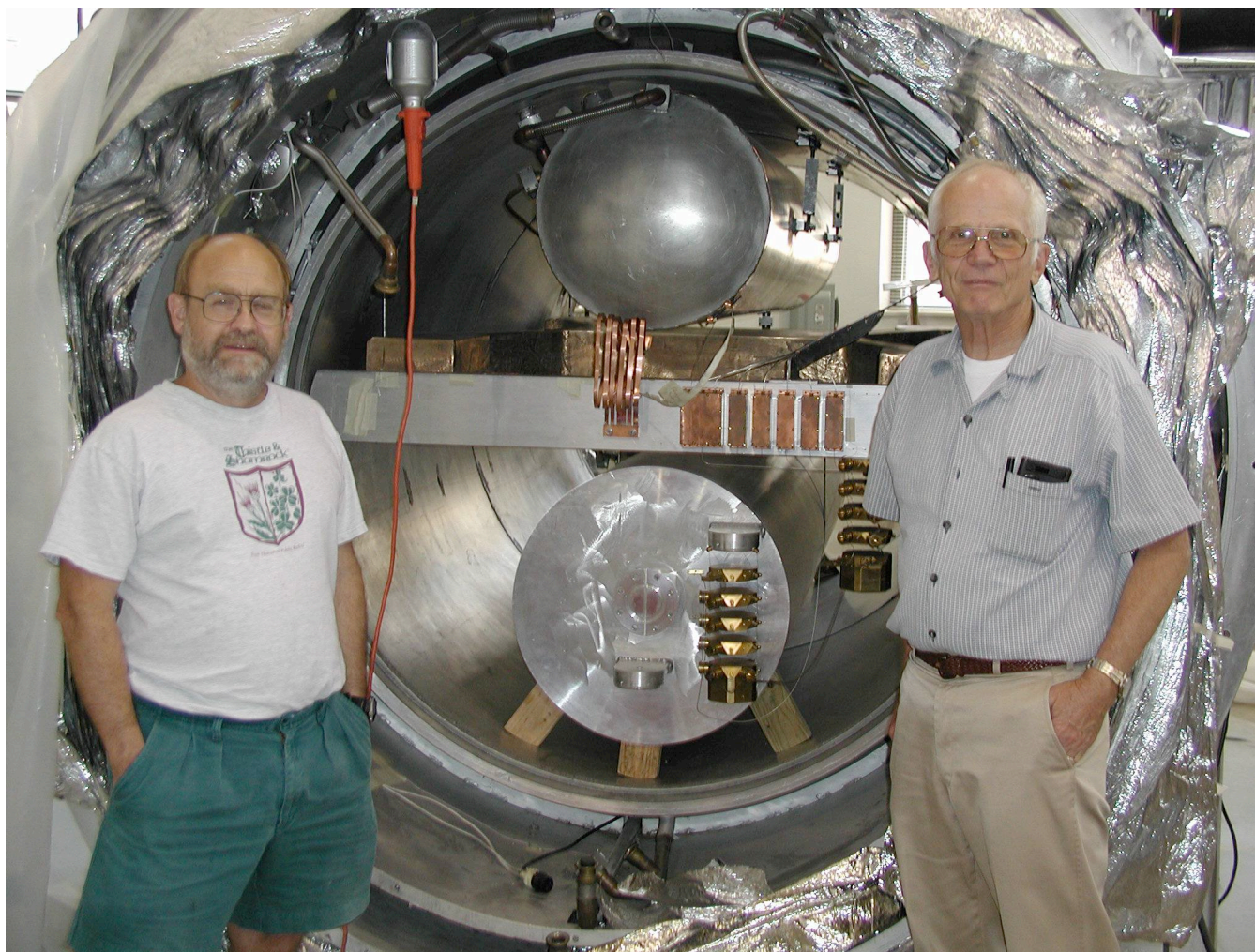


Amplitude of a 1ms burst  
 $\text{SNR}=4.5 \rightarrow h \sim 1.4 \cdot 10^{-18}$

# Explorer/Nautilus

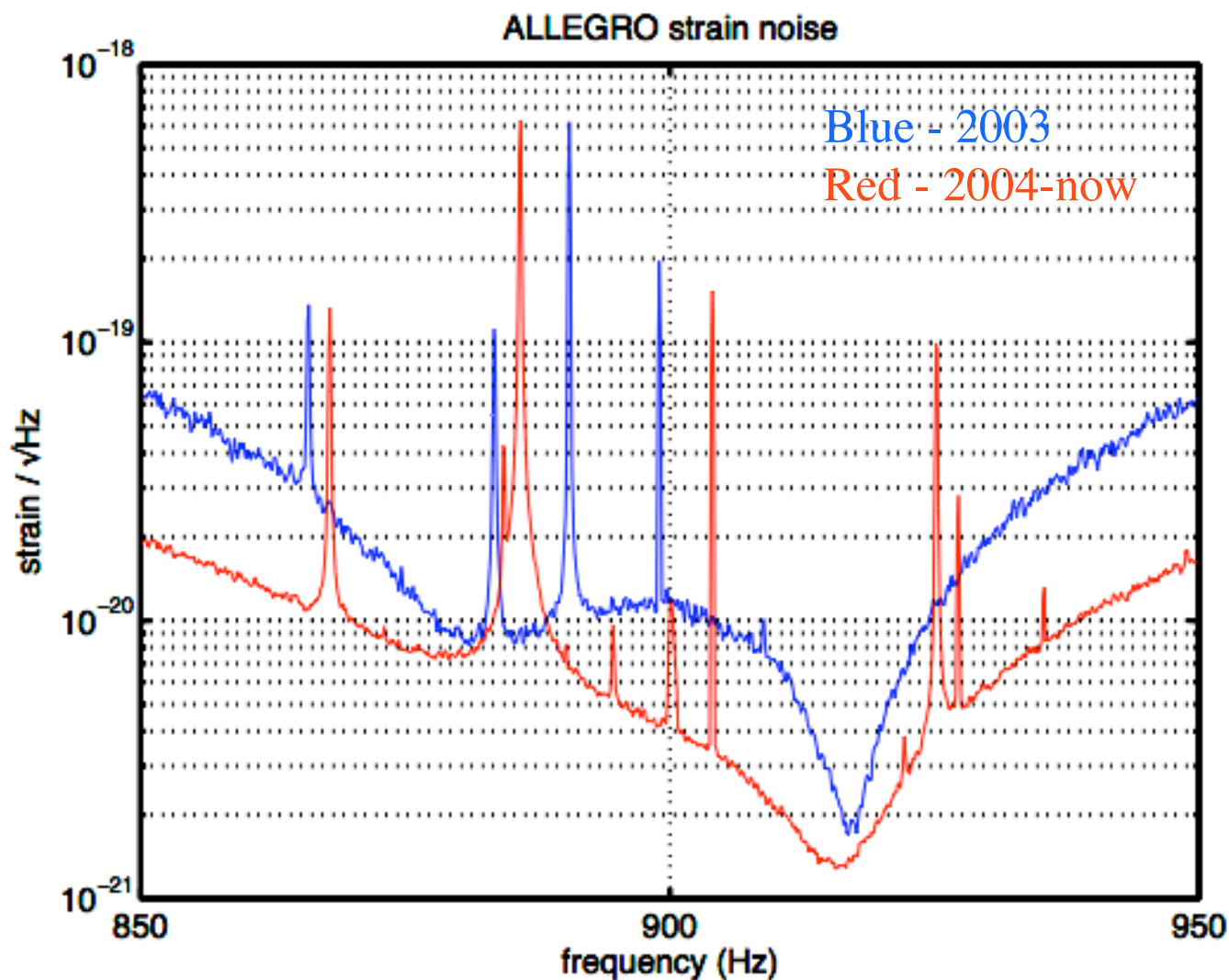


Running with 97%  
duty factor,  
since March 2004



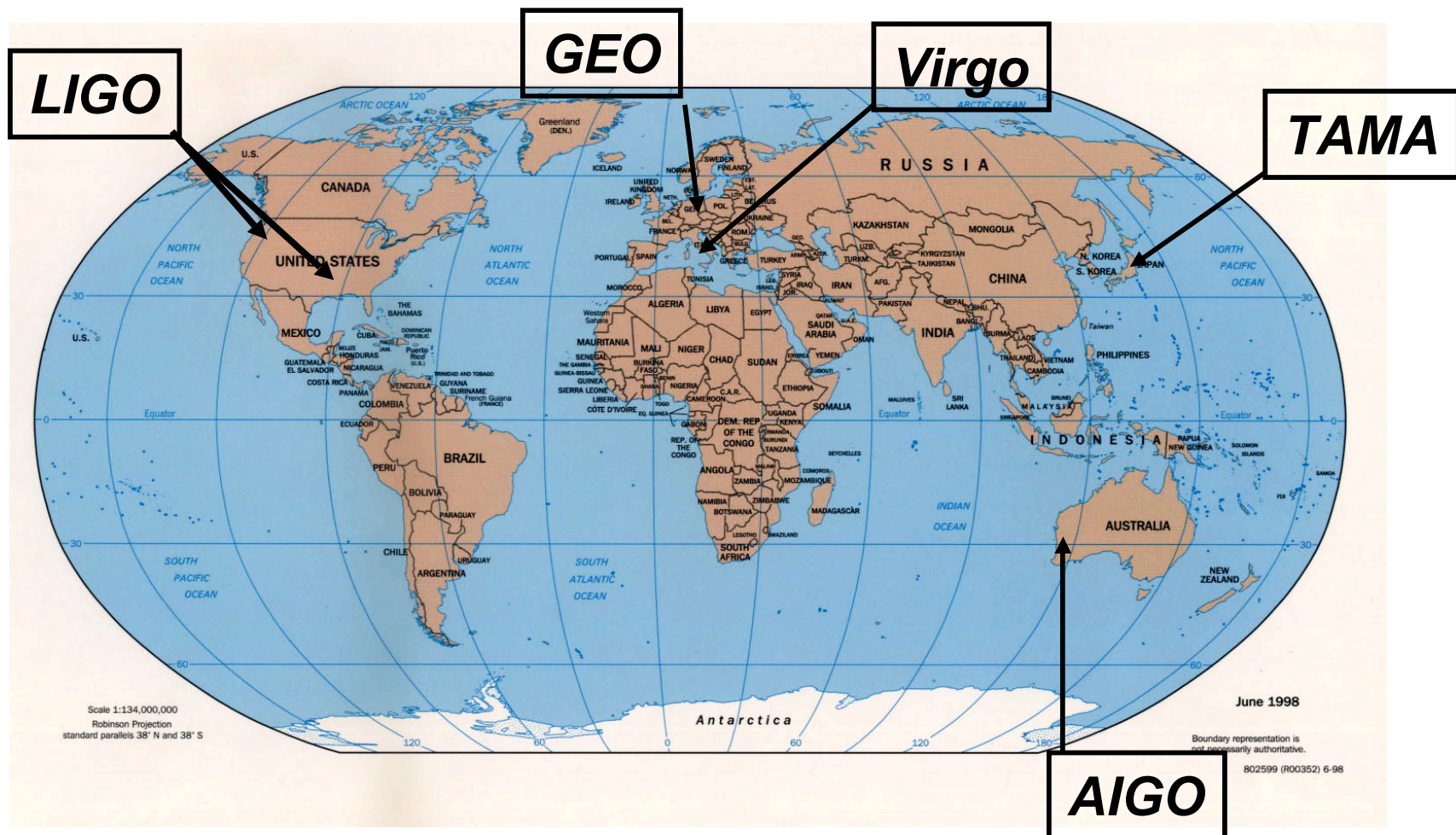


# ALLEGRO Sensitivity





# Global Network of Interferometers



LIGO-G060291-00-Z



# Status of interferometers



---

The global network of 2006 – 2008 will center on LIGO, GEO, and Virgo.

LIGO: 3 interferometers at 2 4 km sites  
(Hanford WA and Livingston LA)

GEO: 600 m interferometer near Hannover

Virgo: 3 km interferometer near Pisa

TAMA 300 (Japan) has operated well, and is now undergoing upgrades.

AIGO (Australia) is a lab for advanced interferometer technology, and (it is hoped) a site for a future large interferometer.



# LIGO



(here, LIGO Livingston Observatory)

A 4-km Michelson interferometer, with mirrors on pendulum suspensions.

Site at Hanford WA has both 4-km and 2-km.

Scientific operations began Nov 2005, at design sensitivity:

$$h_{rms} = 10^{-21}.$$





**LIGO**

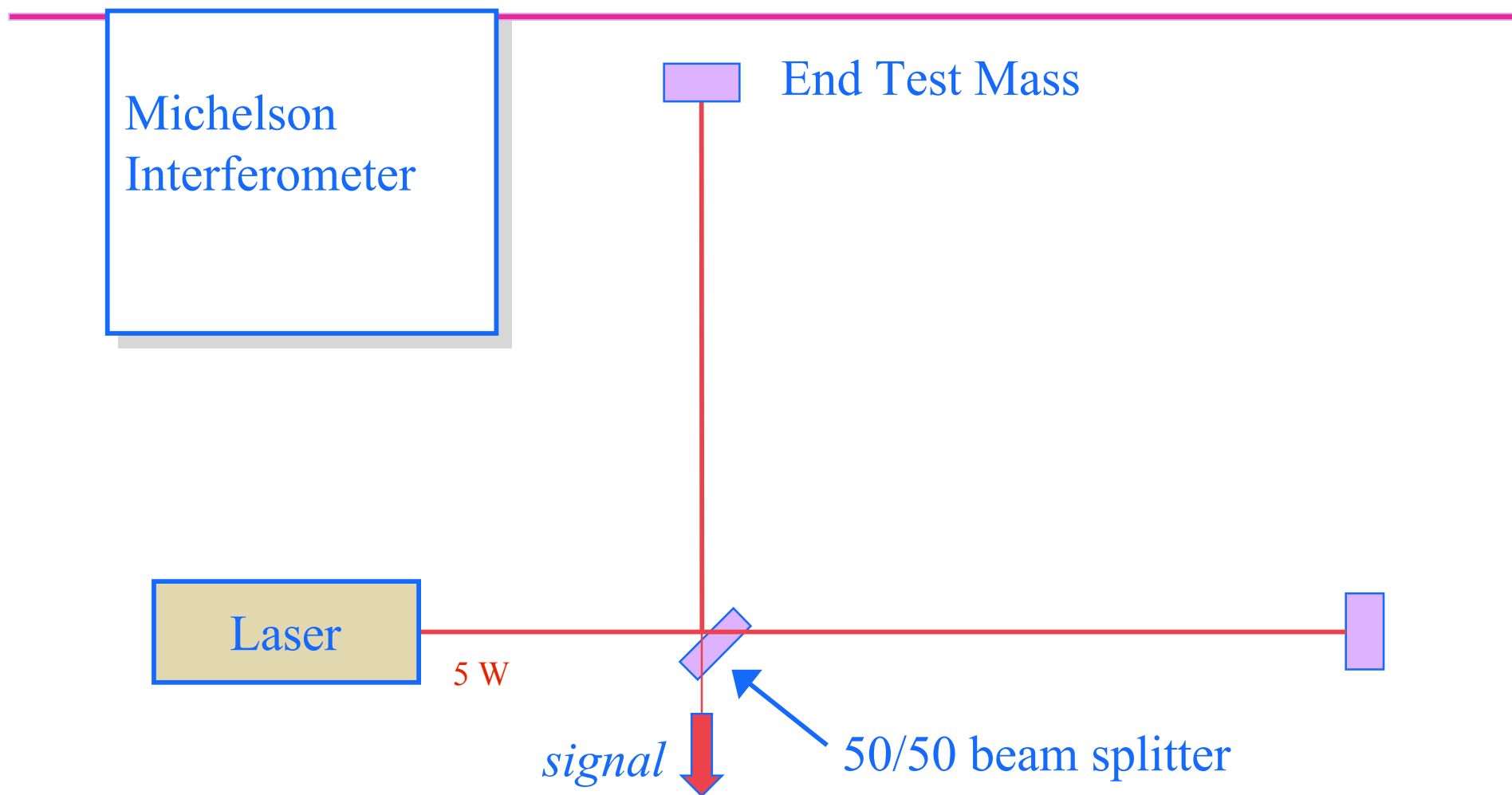
# LIGO Hanford Observatory



*LIGO-G060291-00-Z*

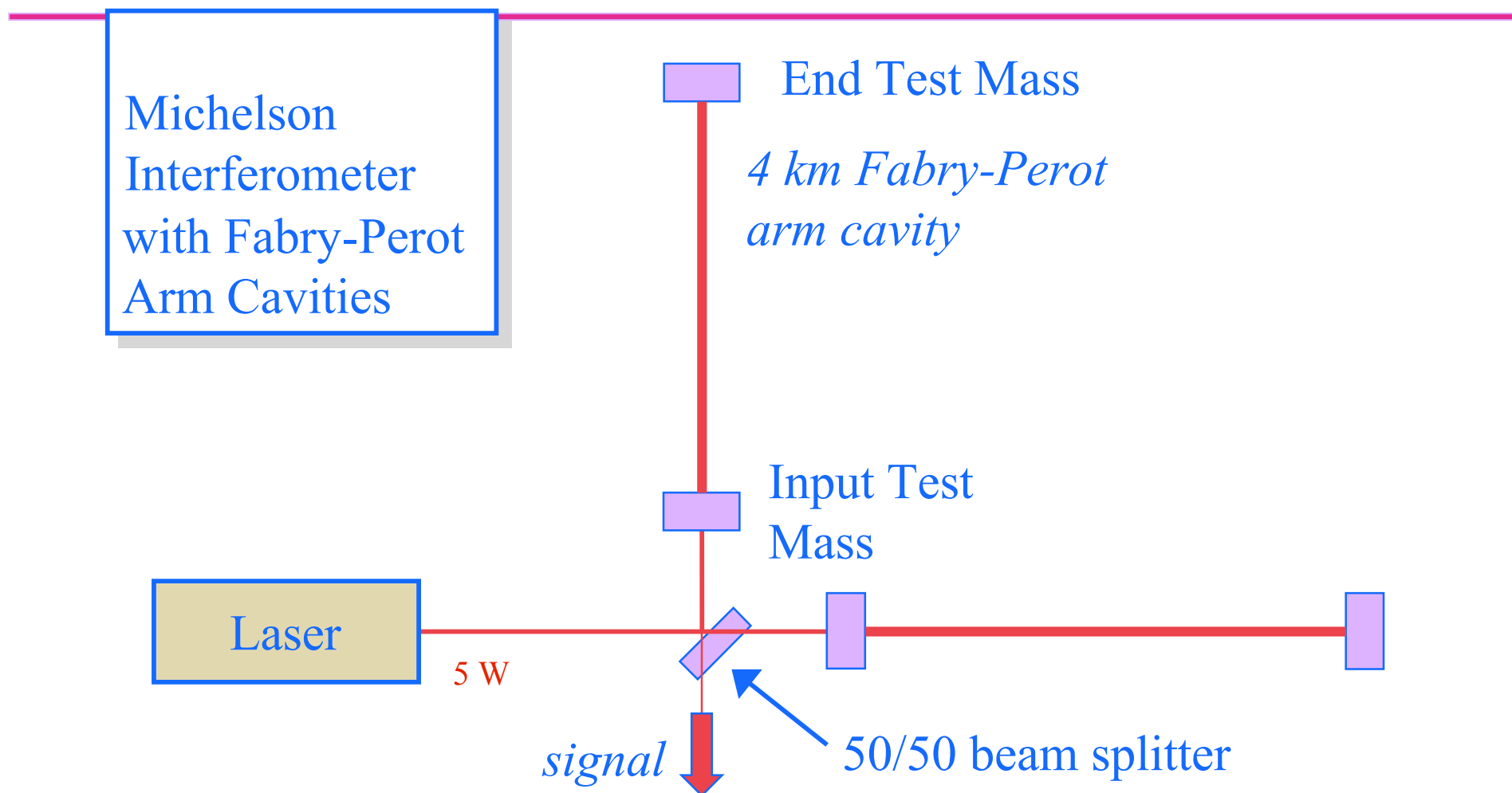


# LIGO LIGO Optical Configuration





# LIGO Optical Configuration

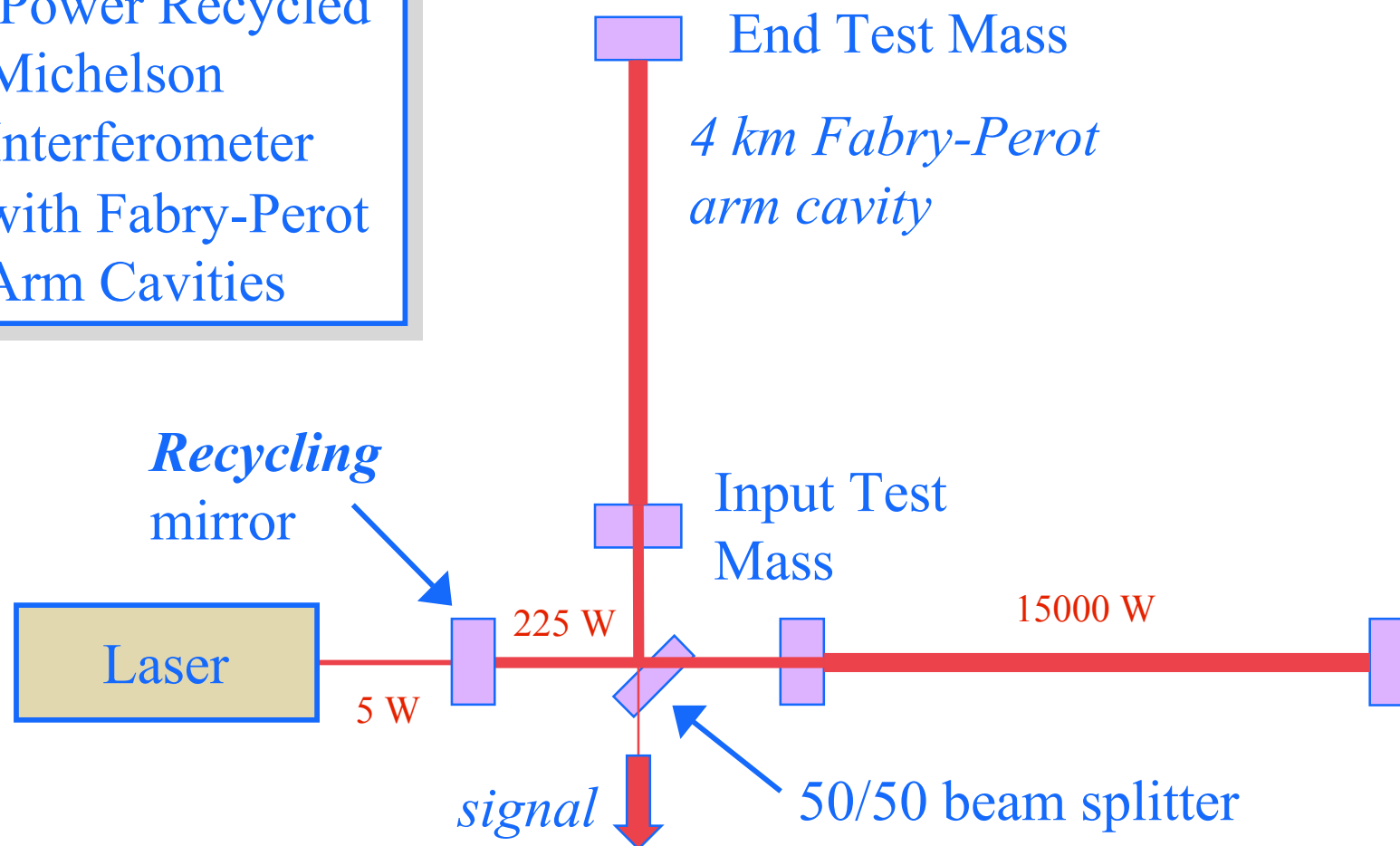




# LIGO LIGO Optical Configuration



Power Recycled  
Michelson  
Interferometer  
with Fabry-Perot  
Arm Cavities

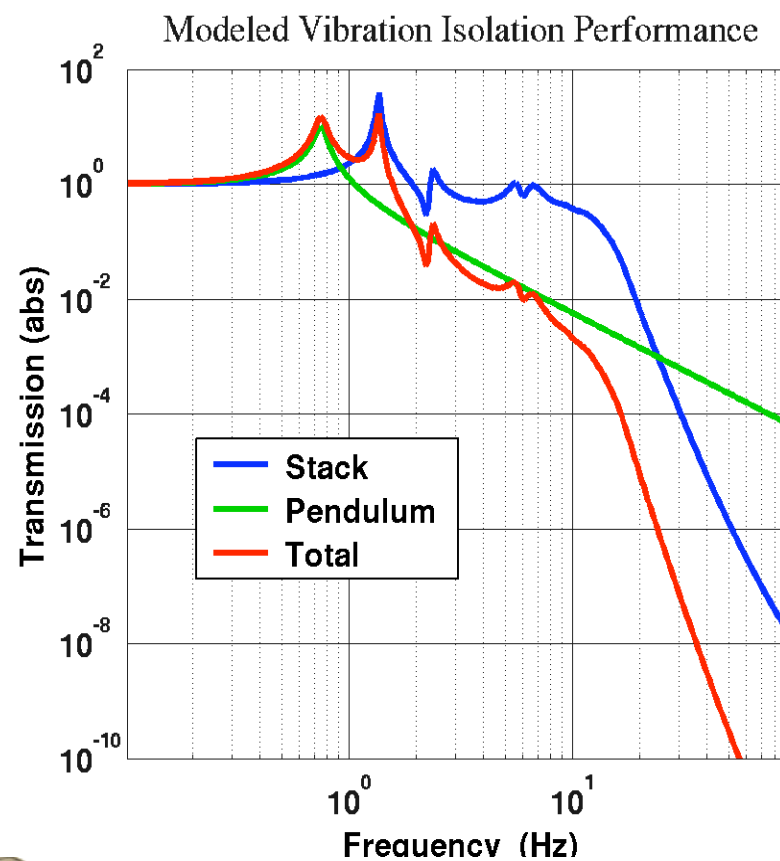
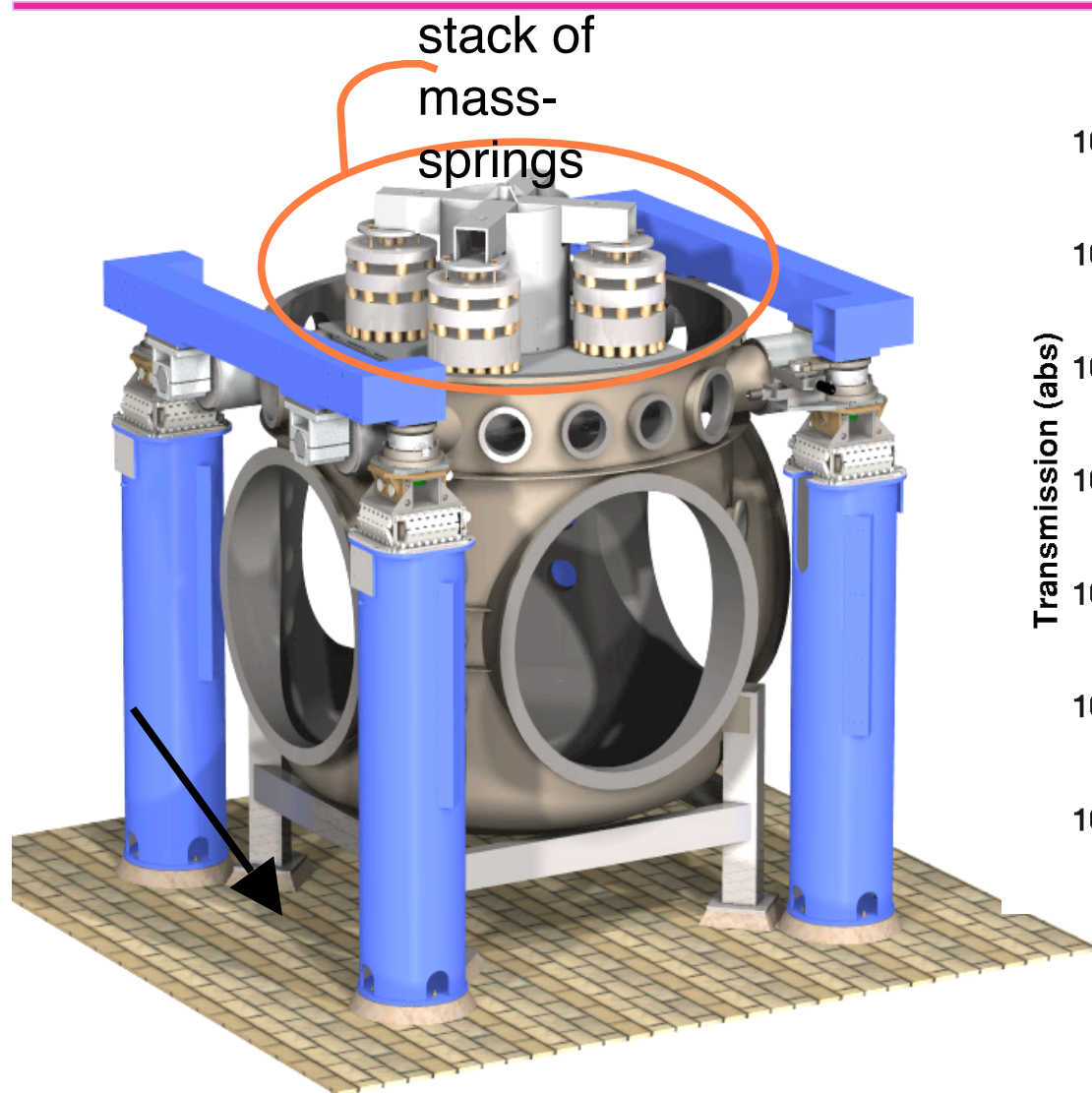




*LIGO-G060291-00-Z*

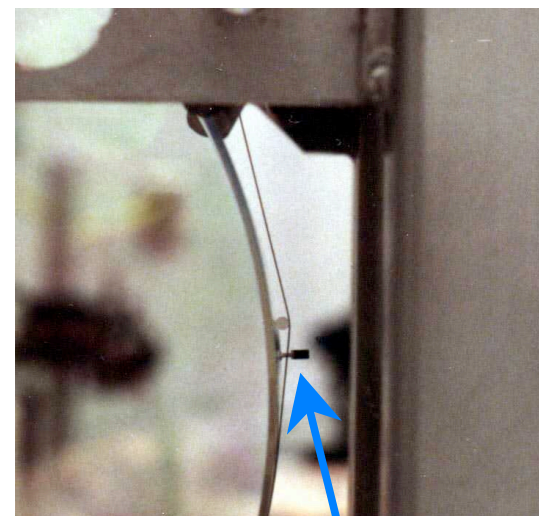
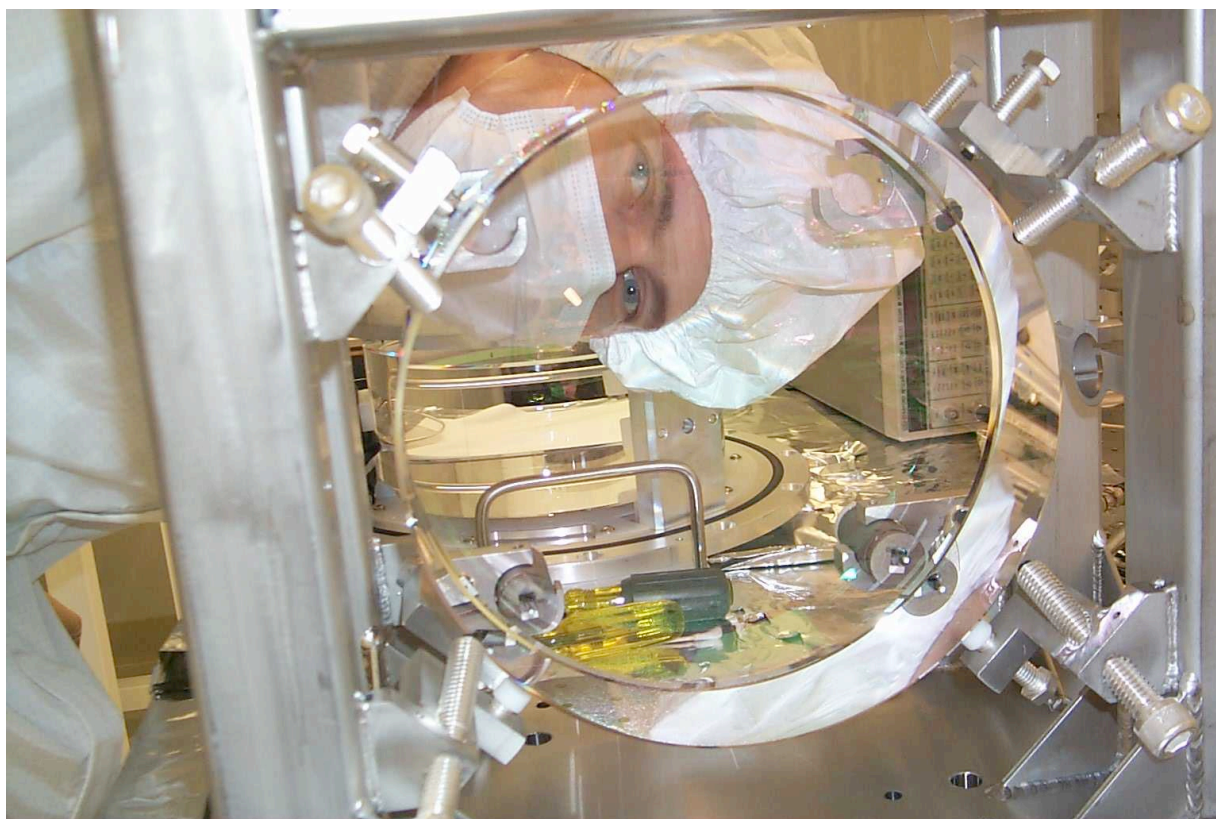


*LIGO-G060291-00-Z*



# Mirror Suspensions

10 kg Fused Silica, 25 cm diameter and 10 cm thick



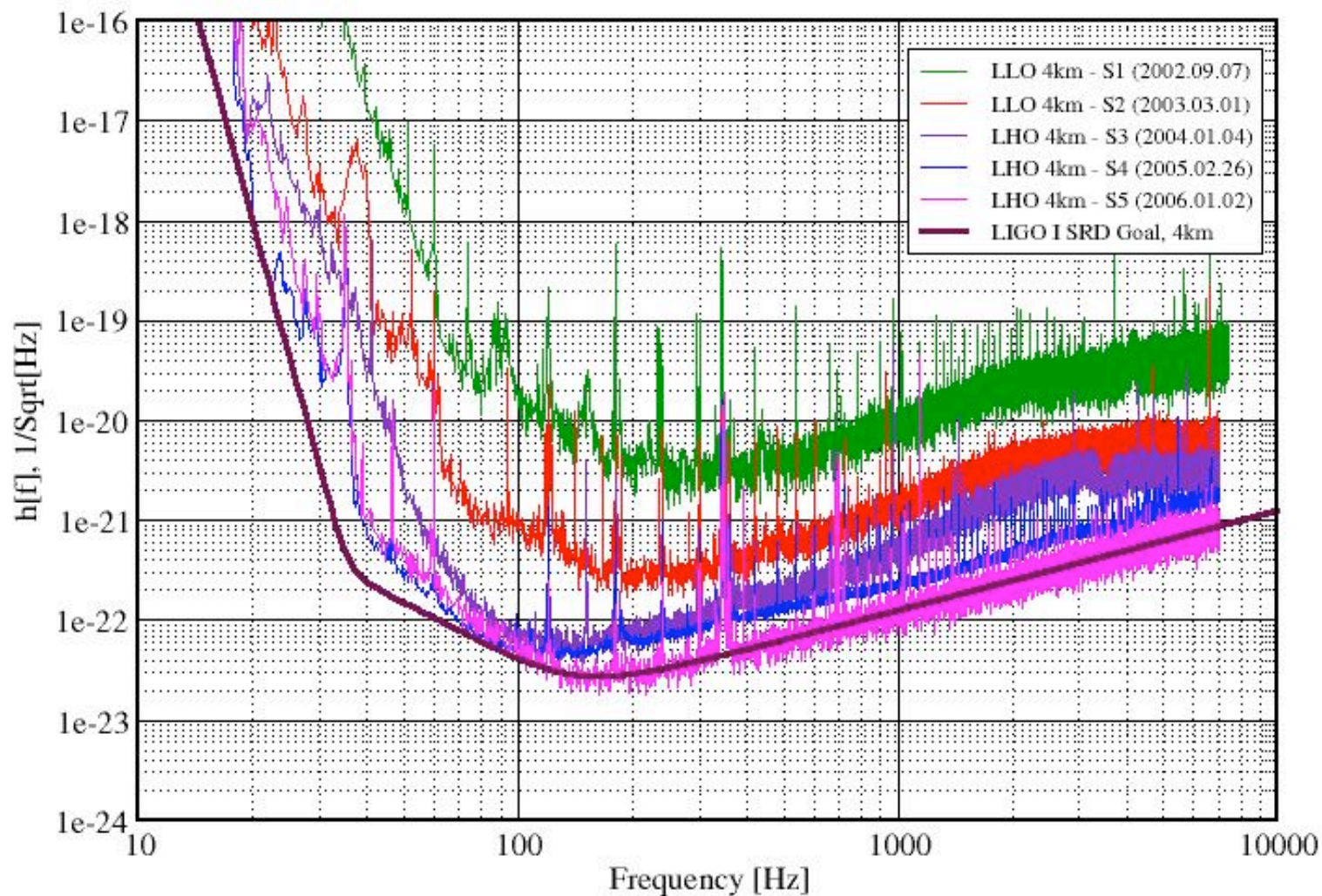
magnet



# LIGO sensitivity over time

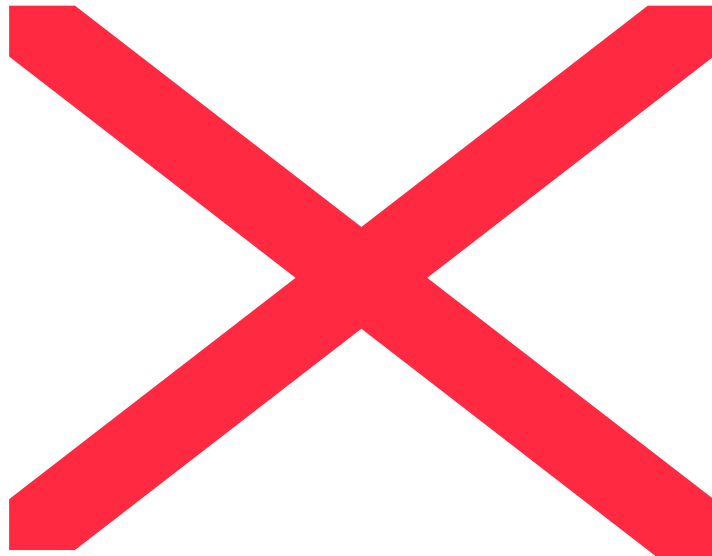
## Best Strain Sensivities for the LIGO Interferometers

Comparisons among S1 - S5 Runs LIGO-G060009-01-Z

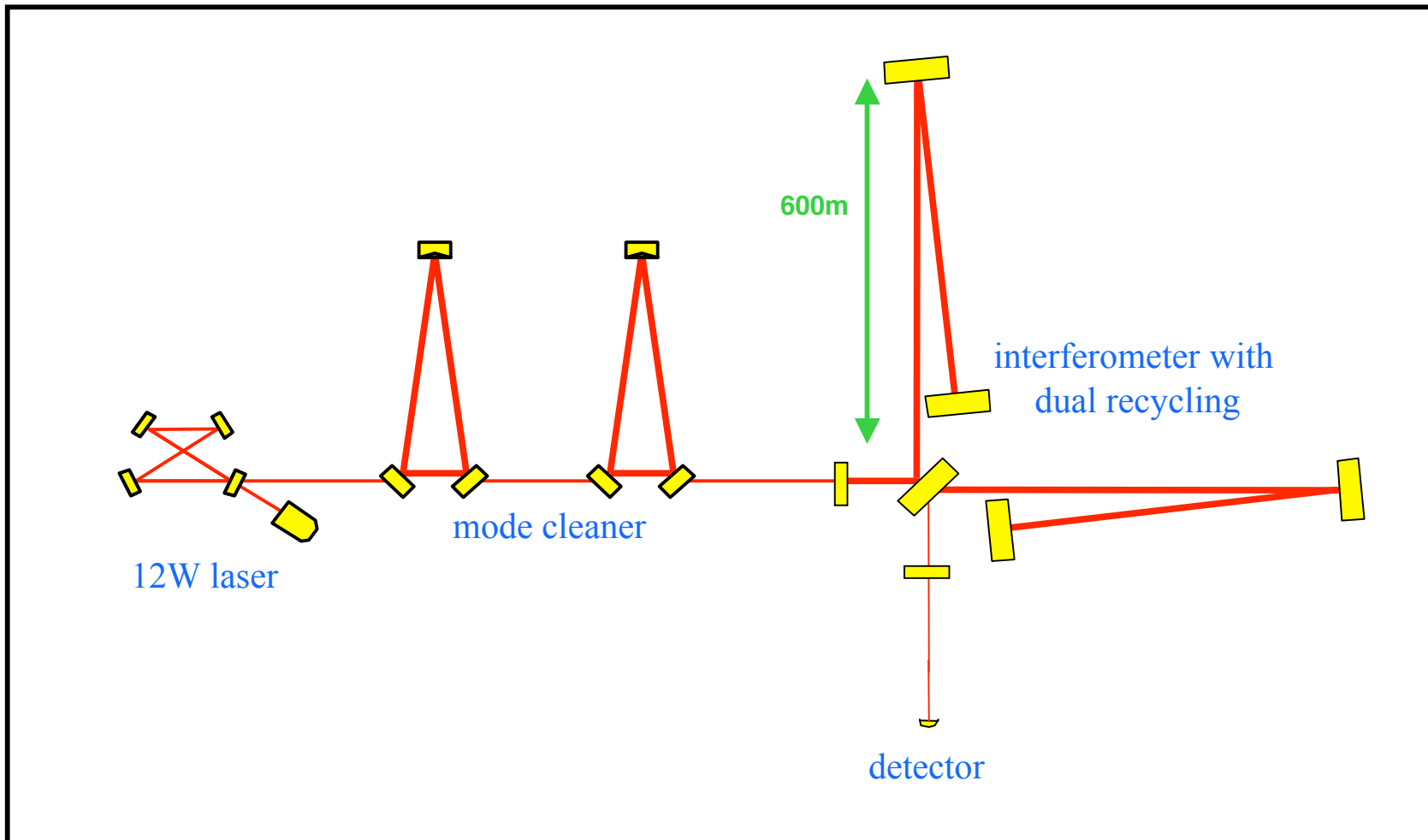




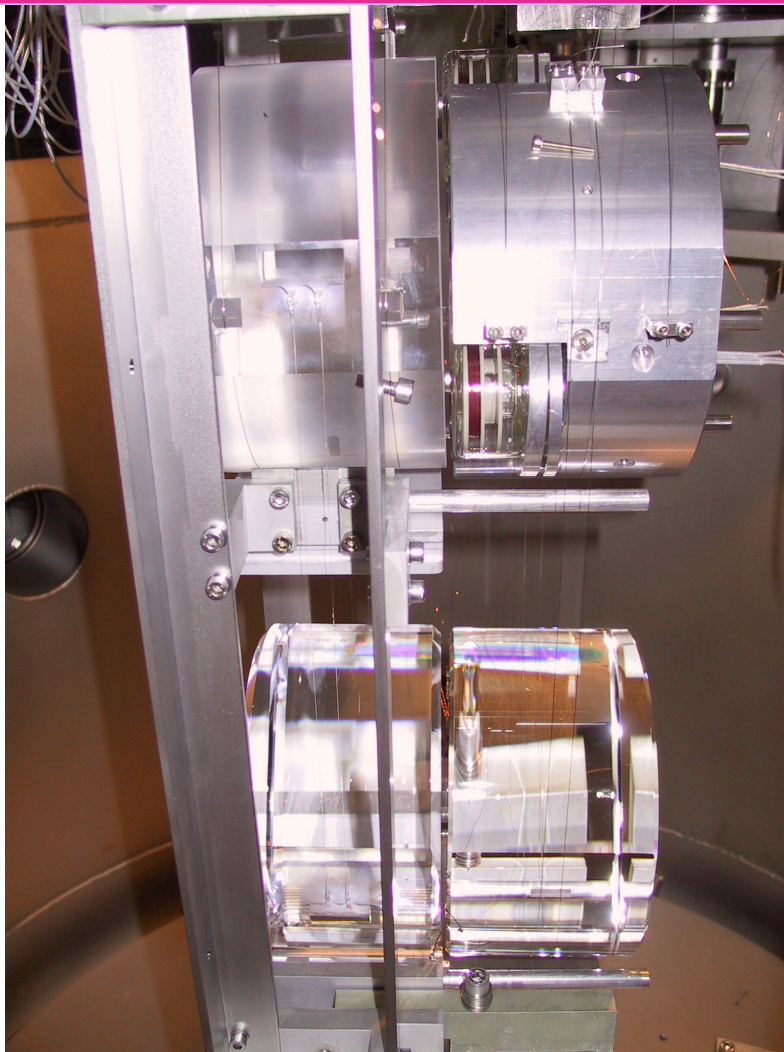
# Recent noise budget, Livingston 4 km interferometer



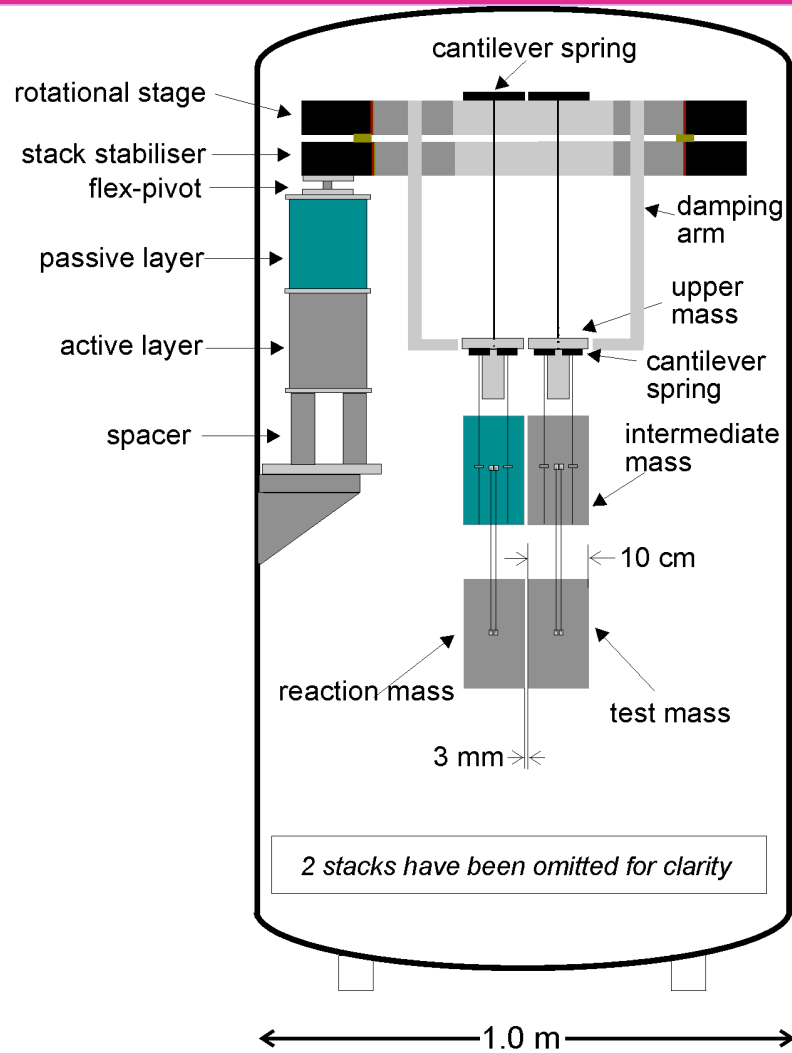




# GEO all-silica pendulum

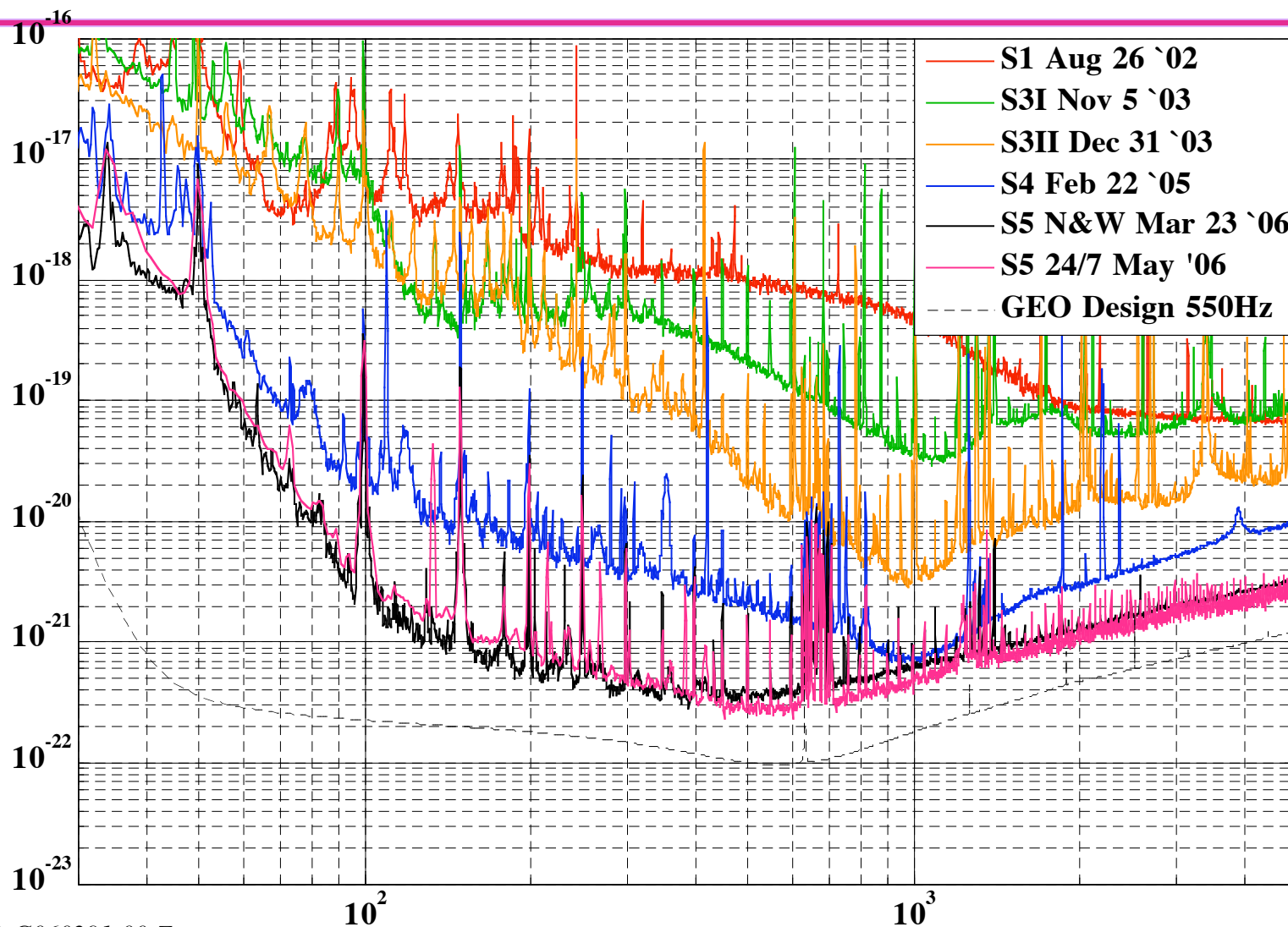


LIGO-G060291-00-Z





# GEO Sensitivity in Science Runs



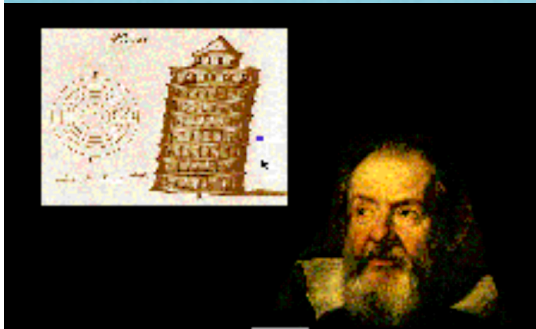
LIGO-G060291-00-Z



## GEO status



- 
- Within  $\sim x3$  of design sensitivity over wide band.
  - Now engaged in full-time observing.
  - Another commissioning period in late 2006 to reach design sensitivity.

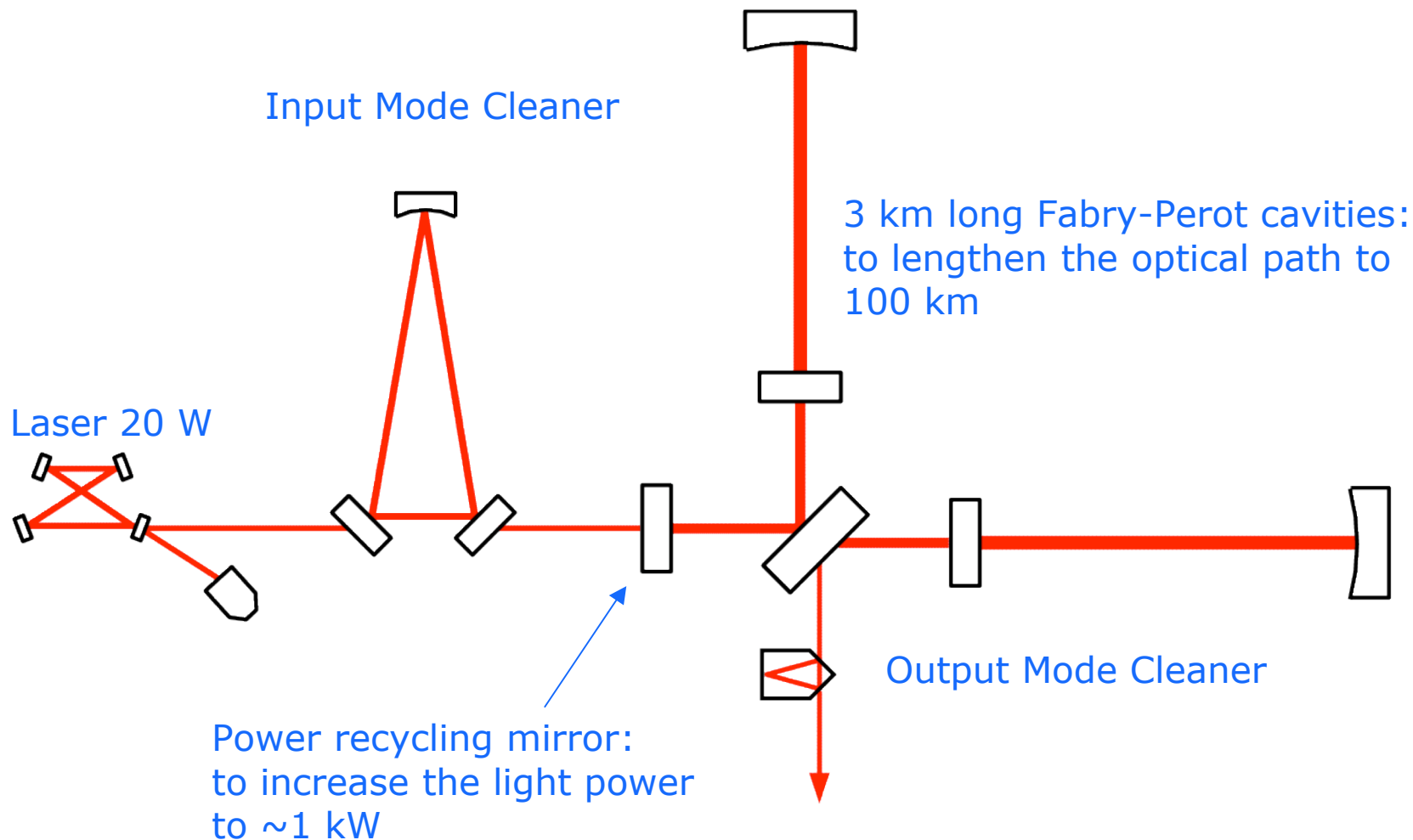


- LAPP - Annecy
- INFN - Firenze/Urbino
- INFN - Frascati
- IPN - Lyon
- INFN - Napoli
- OCA - Nice
- ESPCI - Paris
- LAL - Orsay
- INFN - Perugia
- INFN - Pisa
- INFN - Roma

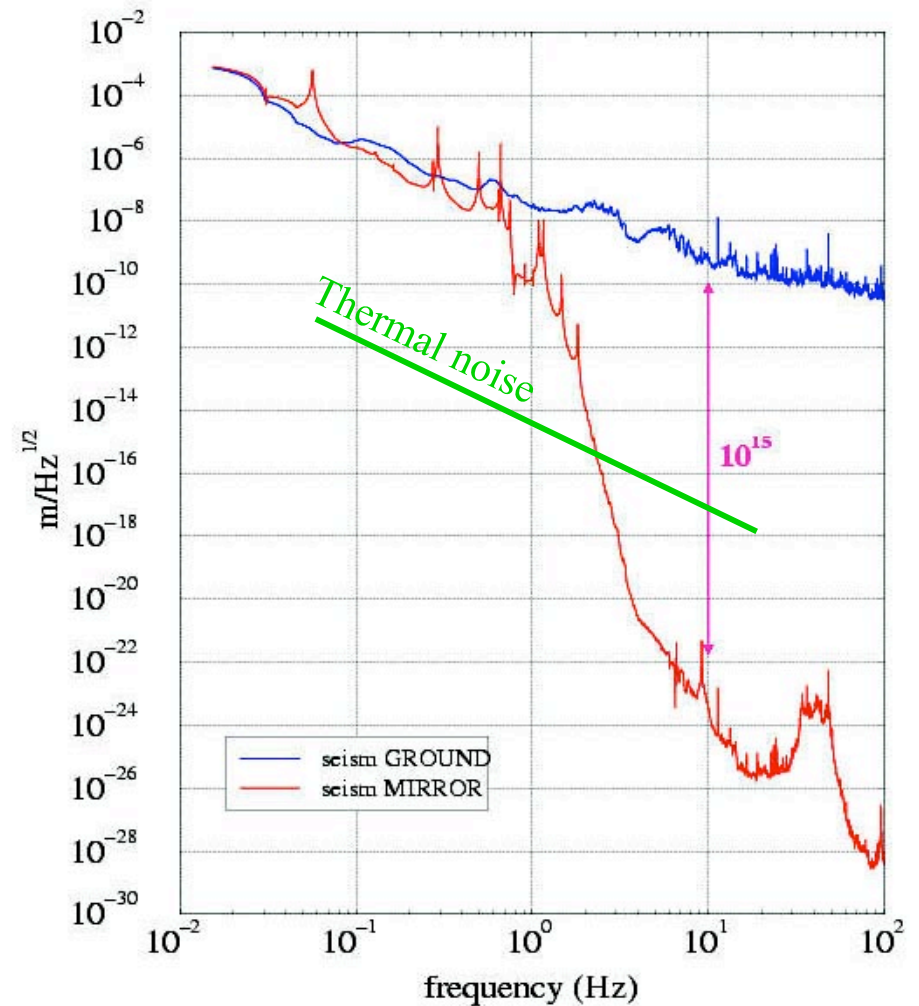
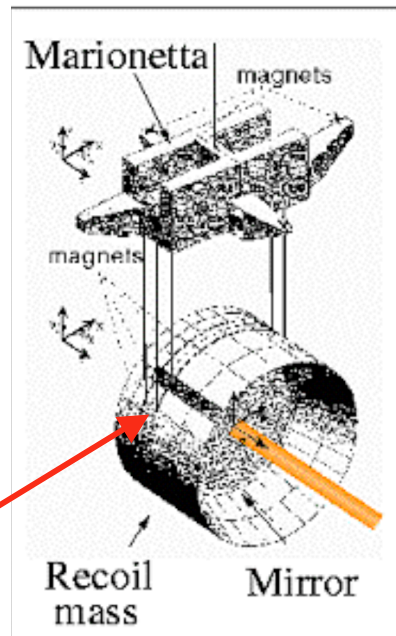
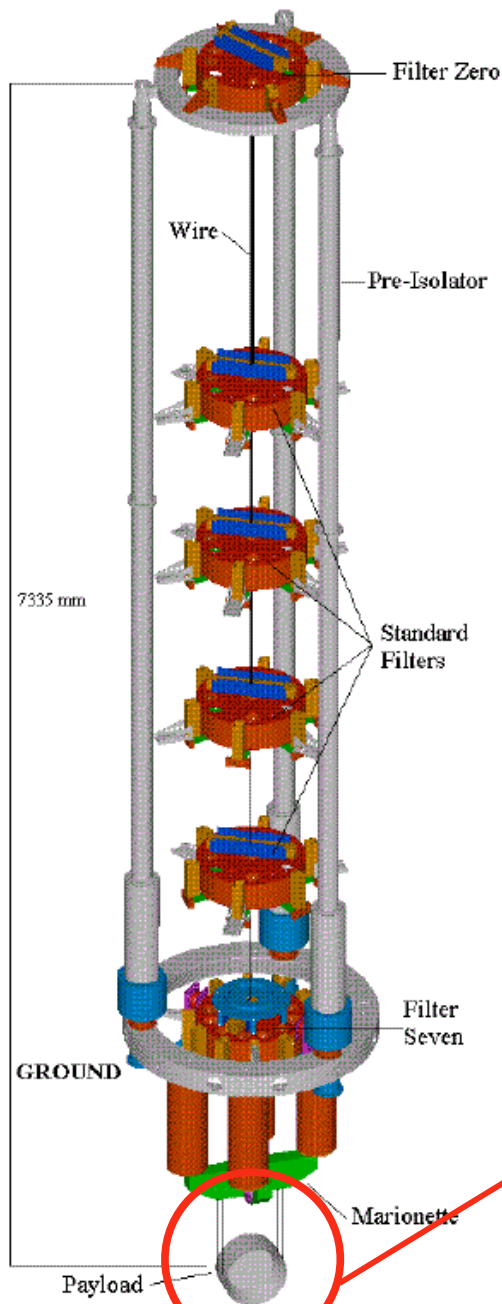
NIKHEF – Amsterdam (joining)

*Inaugurated July 2003*

# Virgo Optical Scheme

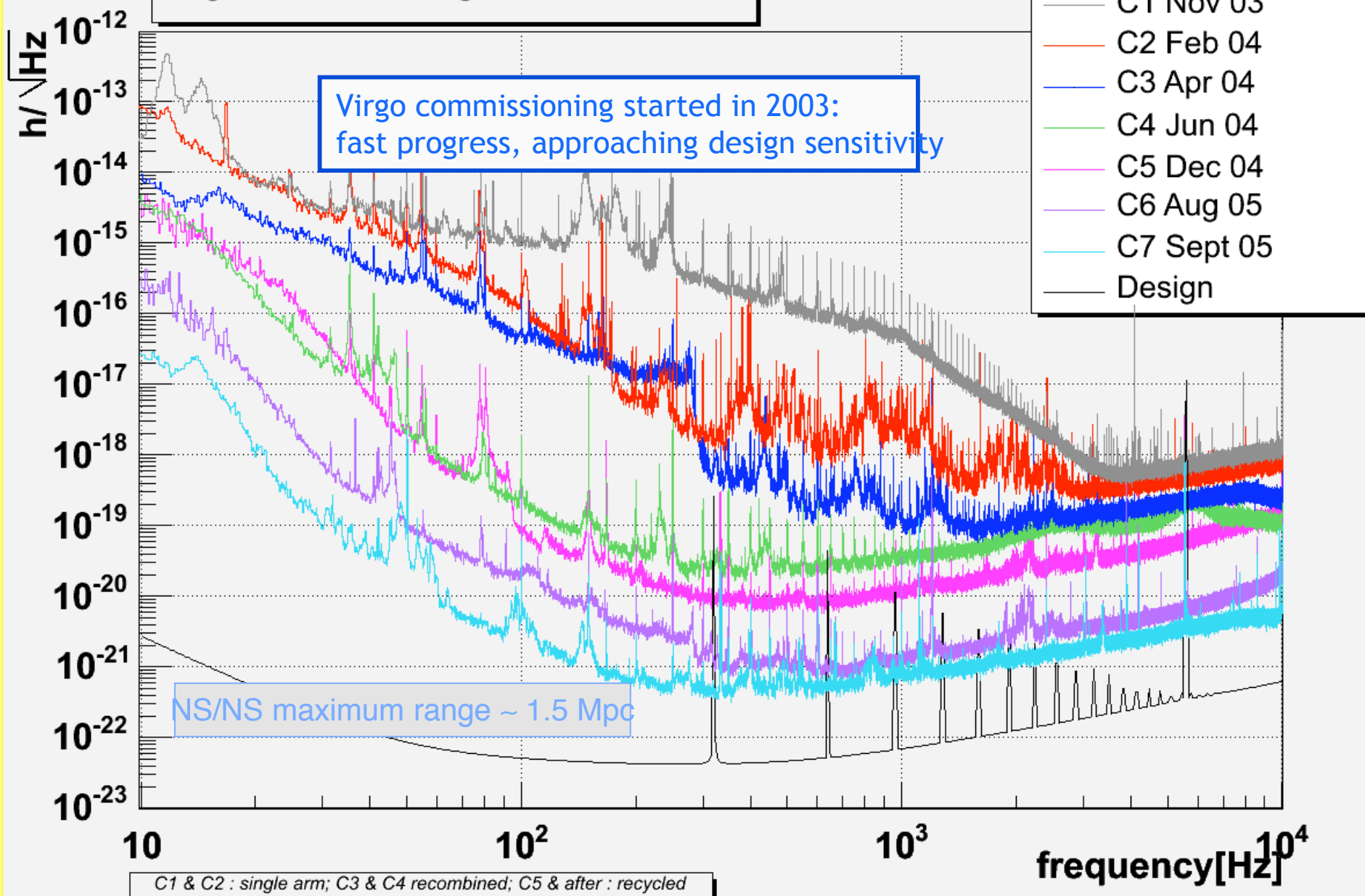


# Virgo Super-Attenuator



LIGO-G060291-00-Z

# Virgo Commissioning Runs Sensitivities





## Virgo status



- 
- Now in commissioning.
  - Expecting to be within  $\sim x2$  of design sensitivity by Fall 2006, then will commence observing.
  - Another commissioning period in first half of 2007 to reach design sensitivity.

# Observations with the Global Network

- Several km-scale detectors, bars now in operation
- Network gives:
  - » Detection confidence
  - » Sky coverage
  - » Duty cycle
  - » Direction by triangulation
  - » Waveform extraction





# Plans for the global network



- GEO and LIGO carry out all observing and data analysis as one team, the LIGO Scientific Collaboration (LSC).
- LSC and Virgo have almost concluded negotiations on joint operations and data analysis.
- This collaboration will be open to other interferometers at the appropriate sensitivity levels. We will also carry out joint searches with the network of resonant detectors.



# The S5 science run



---

Now, that LIGO has reached design sensitivity, we are collecting data.

Previous science runs had durations of only one or two months. Produced a number of upper limit papers.

S5 is intended to collect one year of integrated coincident data at design sensitivity.

S5 began in November 2005.

Calendar duration depends on duty cycle.

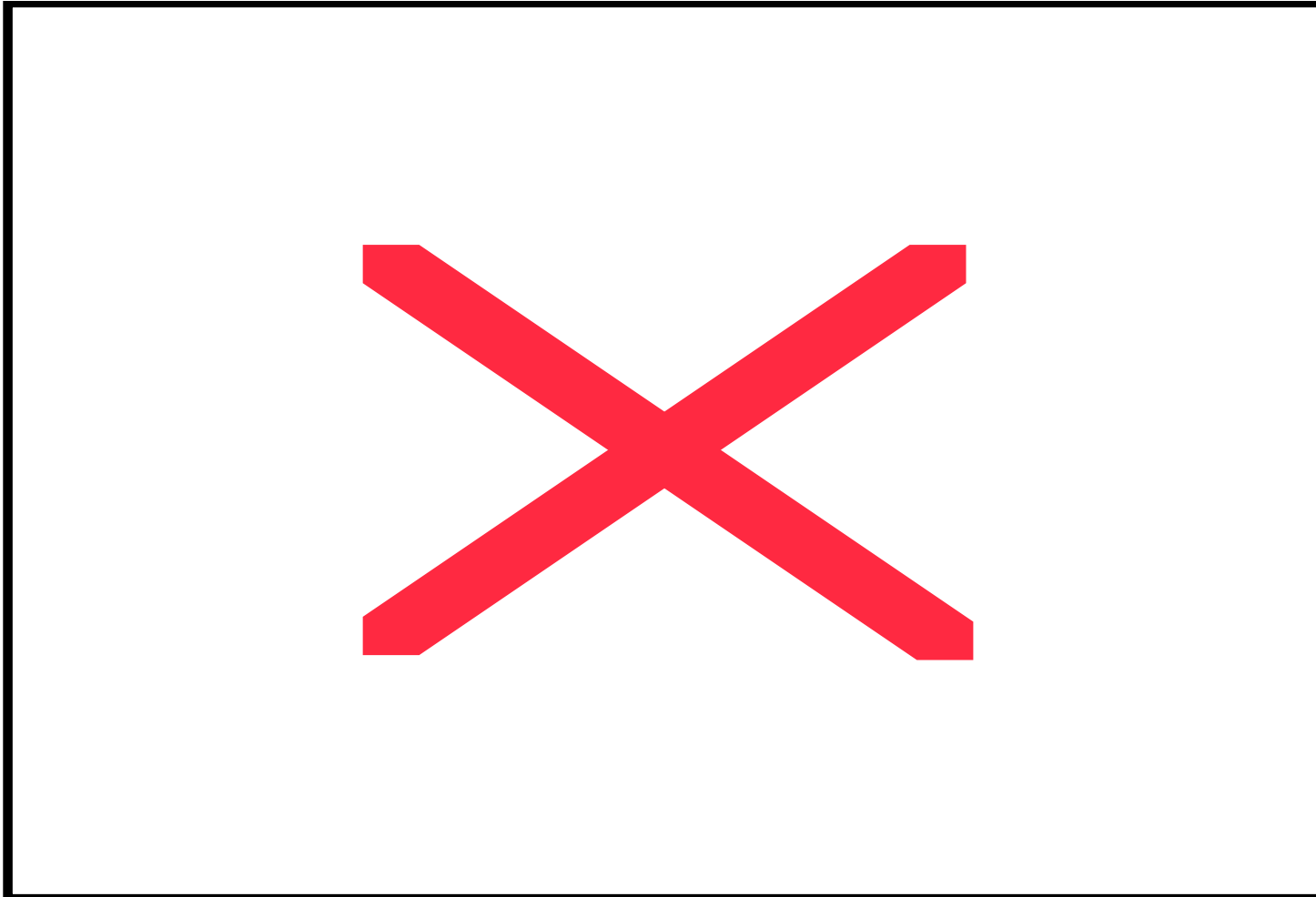
Duty cycle goal is ~70% for triple coincidence.

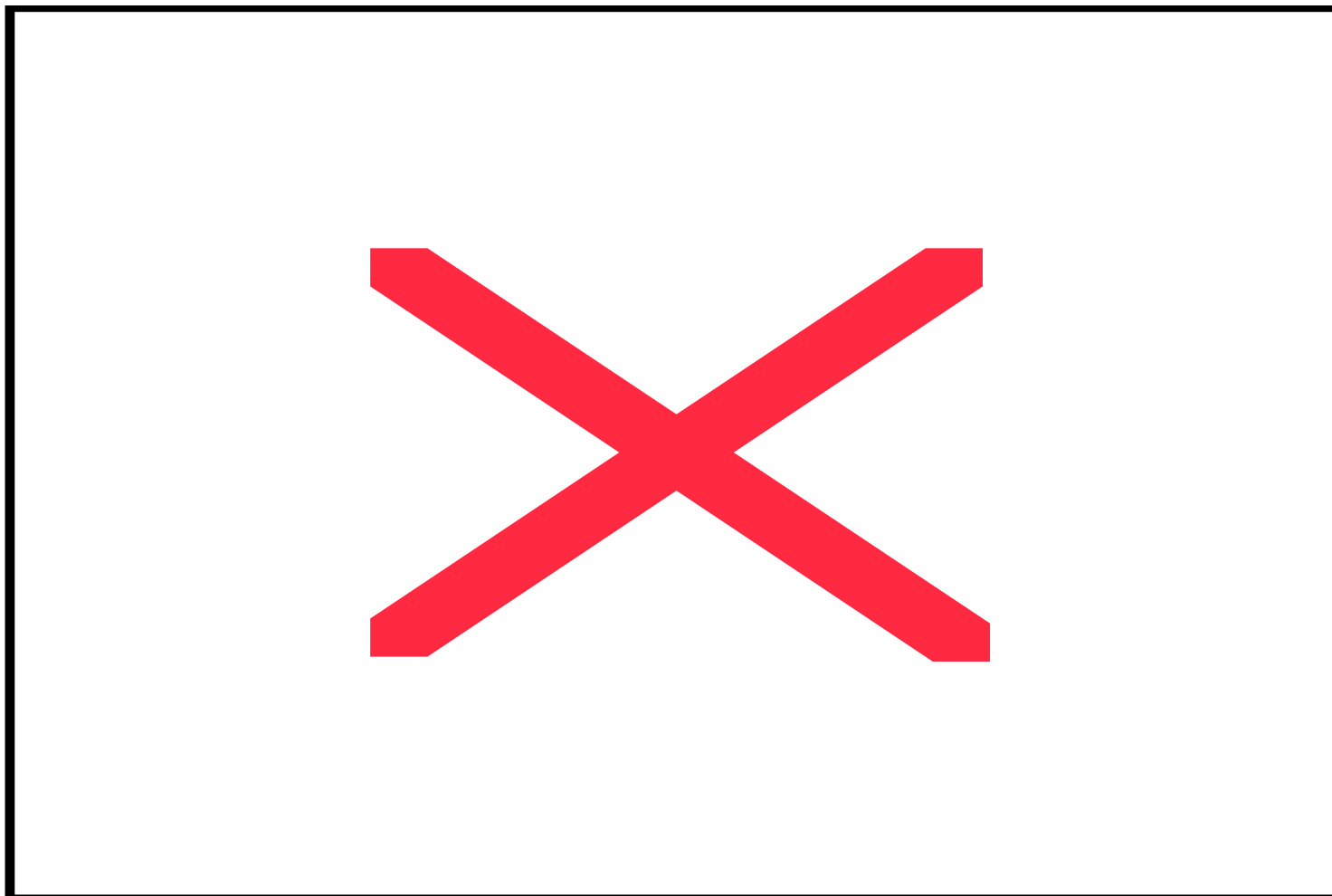
So far, we have achieved about 45%.

GEO has recently joined S5 full time, after commissioning and evening/weekend running.

# Neutron star binary inspiral range vs. date

---







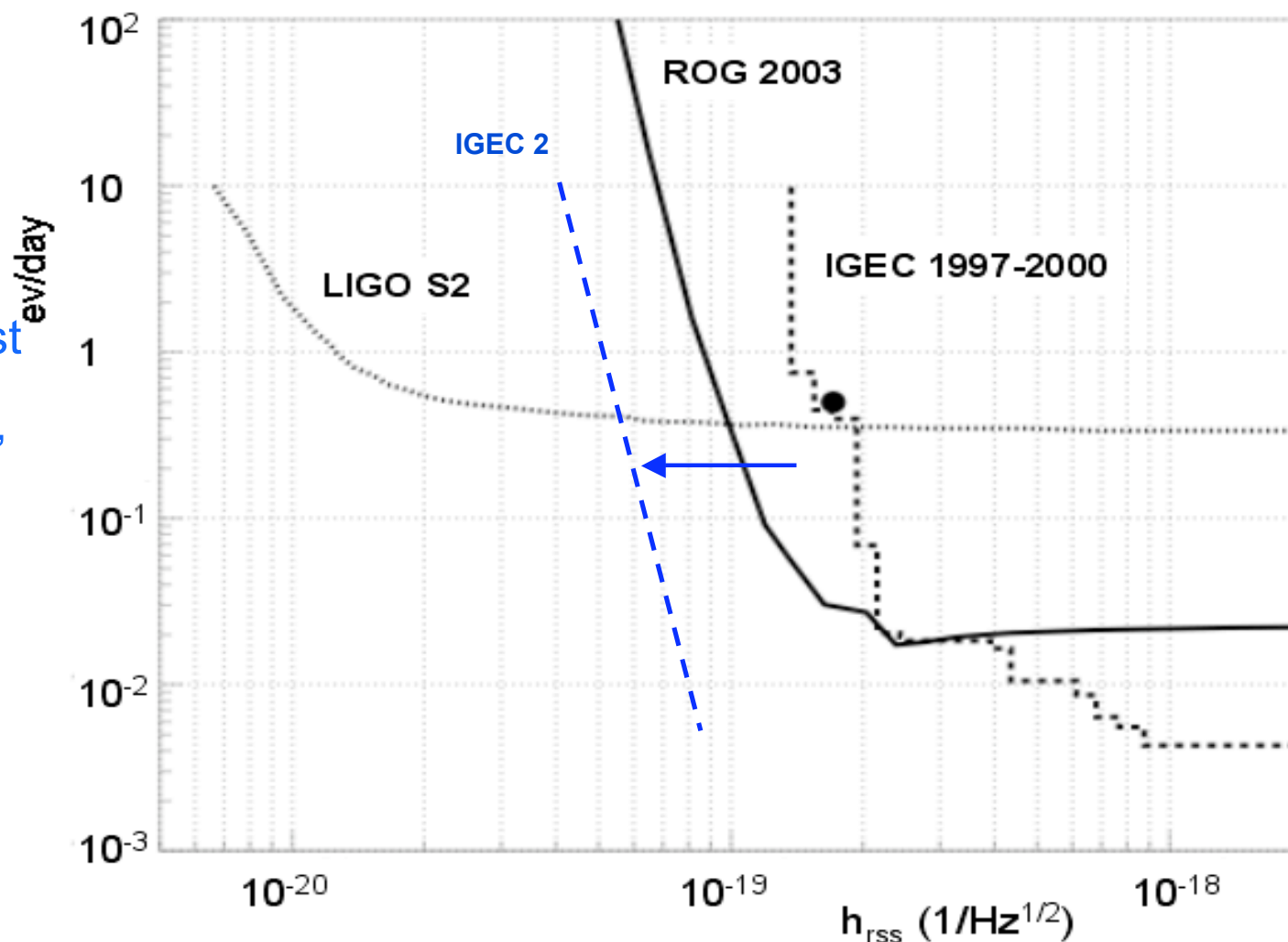
# Past burst upper limits, bars and interferometers



Bars work together as IGEC. New results are expected soon.

LIGO 2003 burst search surpassed bars' sensitivity, but had short observing time.

Sensitivity now over x10 better, integrating for 1 year.



LIGO-G060291-00-Z



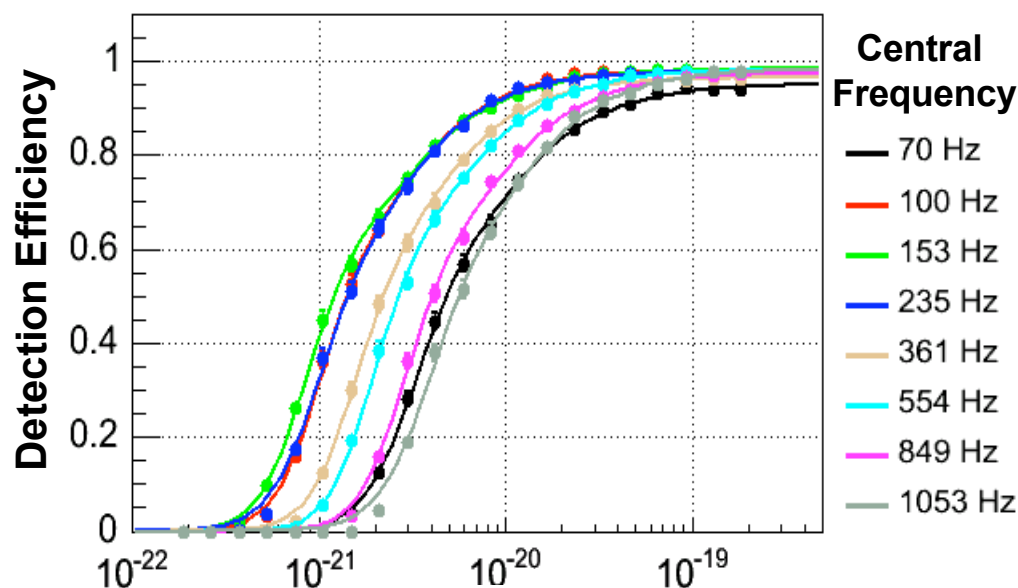
# Untriggered Burst Search



No gravitational wave bursts detected during S1, S2, S3, and S4.

Upper limits set on burst rate and strength from S1, S2, and S4.

Science Run 4



$$h_{\text{rss}} = \sqrt{\int |h(t)|^2 dt}$$

Rapid (high threshold) analysis of first few months of S5 has also not yielded any detections of gravitational wave bursts.

LIGO-G060291-00-Z



# Results from S4 Stochastic Search

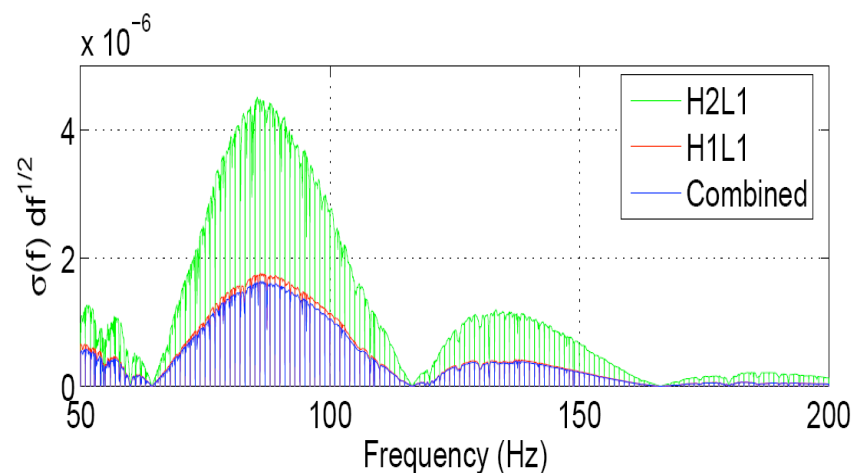
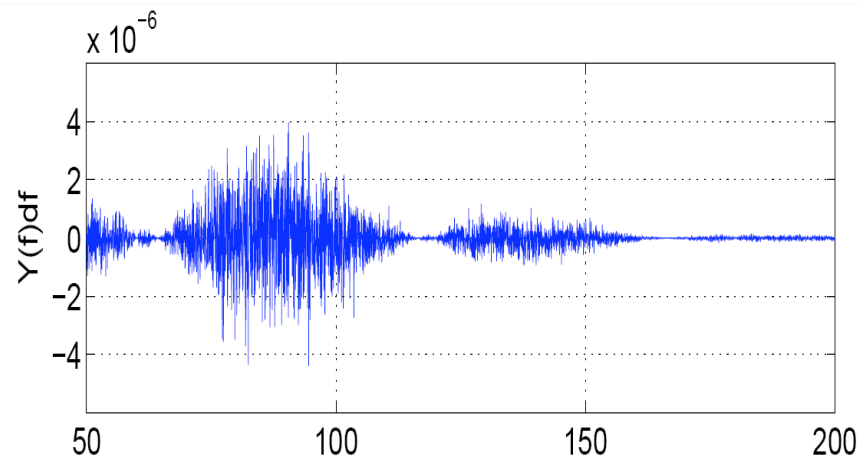


- Weighted average of H1-L1 and H2-L1 measurements:

$$\bar{h} \pm \bar{\sigma} = (-0.8 \pm 4.3) \times 10^{-5}$$

- Bayesian 90% UL:
  - » Use S3 posterior distribution for S4 prior.
  - » Marginalized over calibration uncertainty with Gaussian prior (5% for L1, 8% for H1 and H2).

$$\bar{h}_{90\%} = 6.5 \times 10^{-5}$$





# S5 upper limits on signals from known pulsars



Closest to spin-down upper limit:

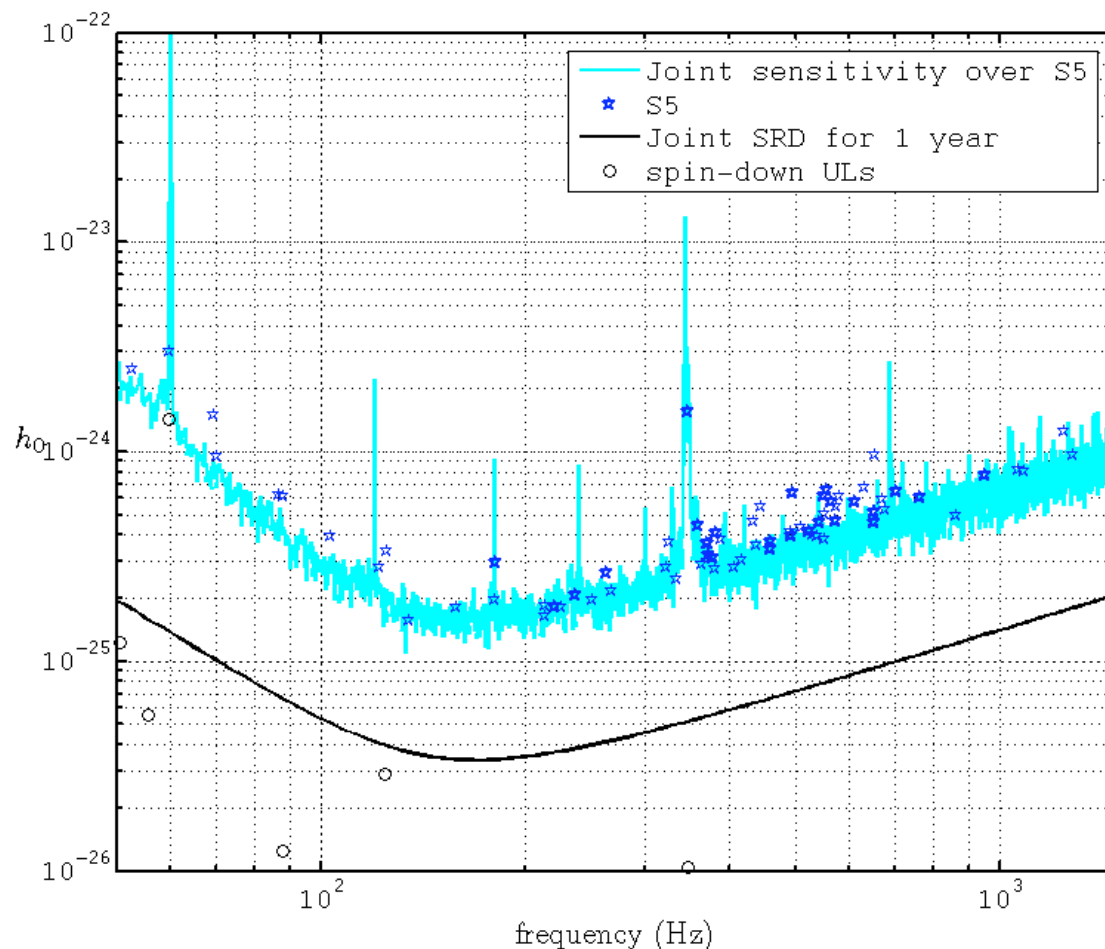
Crab pulsar, only ~ **2.1** times greater than spin-down

$$h_0 = 3.0 \times 10^{-24},$$

$$\varepsilon = 1.6 \times 10^{-3}$$

$$(f_{\text{gw}} = 59.6 \text{ Hz, dist} = 2.0 \text{ kpc})$$

We should have sensitivity below spin-down limit on the Crab pulsar before S5 is over.





# Coming Soon: Advanced LIGO

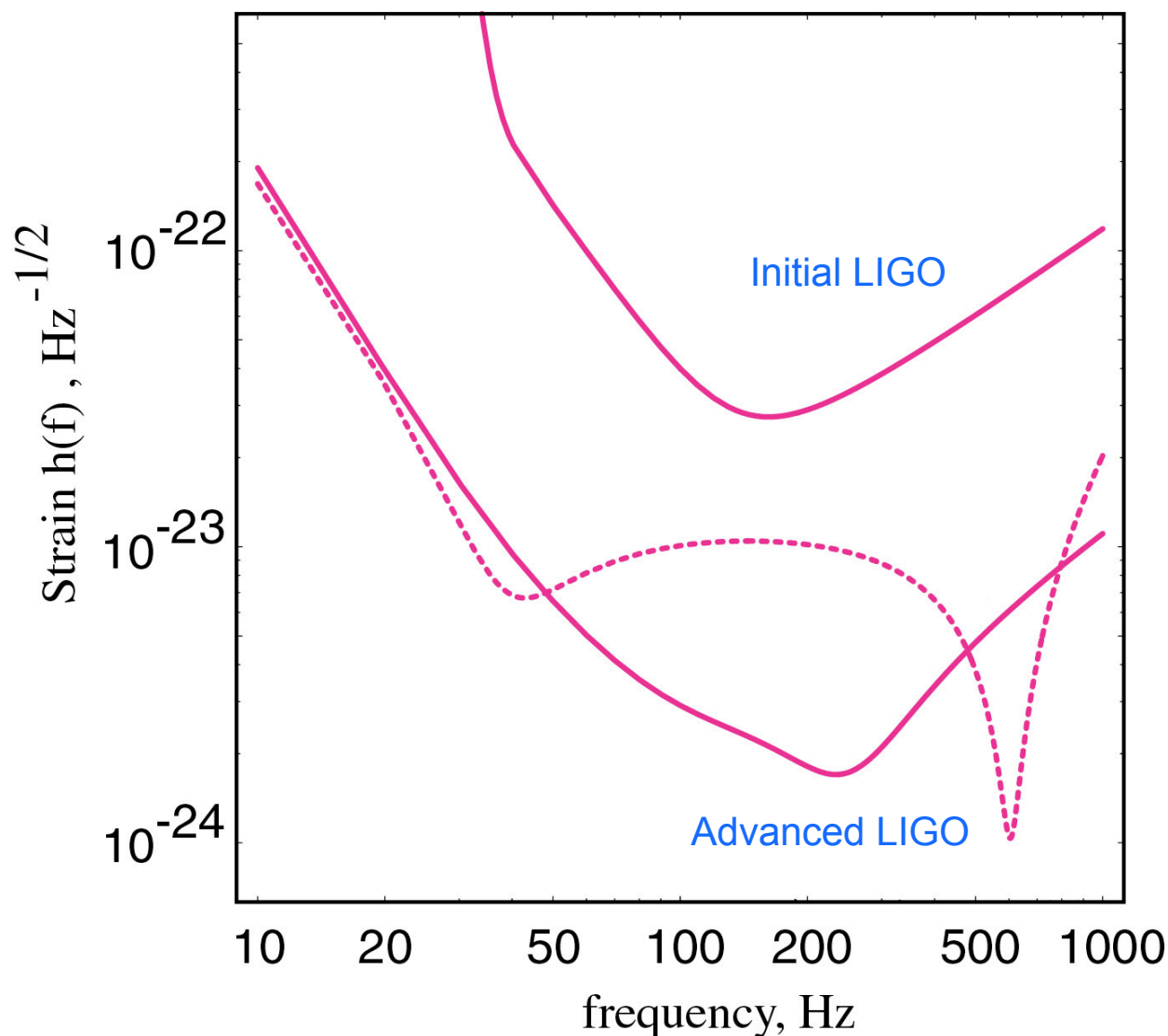


Much better sensitivity:

- ~10x lower noise
- ~4x lower frequency
- tunable

Through these features:

- Fused silica multi-stage suspension
- ~20x higher laser power
- Active seismic isolation
- Signal recycling
- Quantum engineering  
rad'n pressure vs. shot noise





# Reach of advanced interferometers



Advanced LIGO and its cousins (Advanced Virgo, LCGT) are expected to see lots of signals.

- Neutron star binaries
  - » Range = 350 Mpc
  - »  $N \sim 2/(\text{yr}) - 3/(\text{day})$
- Black hole binaries
  - » Range = 1.7 Gpc
  - »  $N \sim 1/(\text{month}) - 1/(\text{hr})$
- BH/NS binaries
  - » Range = 750 Mpc
  - »  $N \sim 1/(\text{yr}) - 1/(\text{day})$

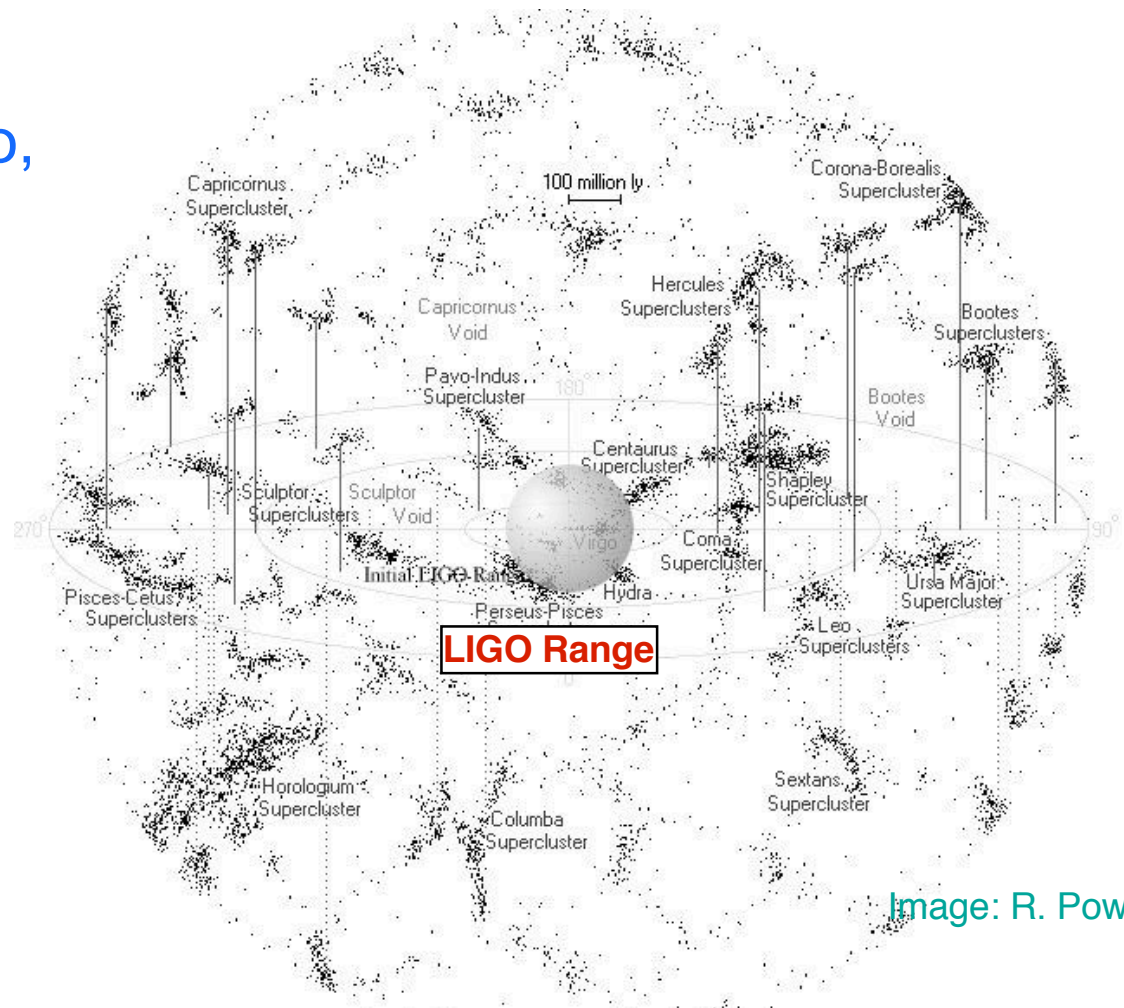


Image: R. Powell



# Status of Advanced LIGO



---

PPARC is funding substantial U.K. contribution (£8M),  
including multi-stage fused silica test mass suspensions.

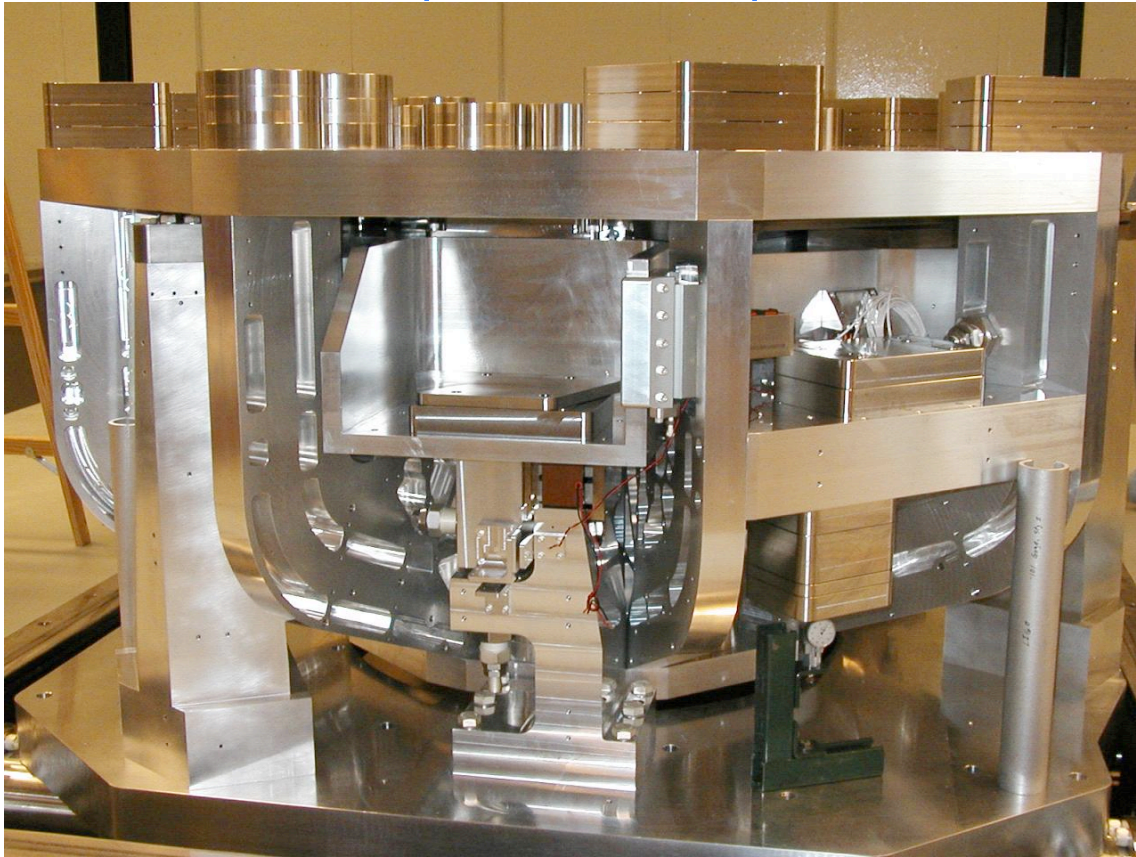
Max Planck Society has endorsed major German  
contribution,  
with value comparable to U.K.'s contribution,  
including 200 W laser.

U.S. National Science Board approved Advanced LIGO.  
We hope funds are included the next U.S. budget.

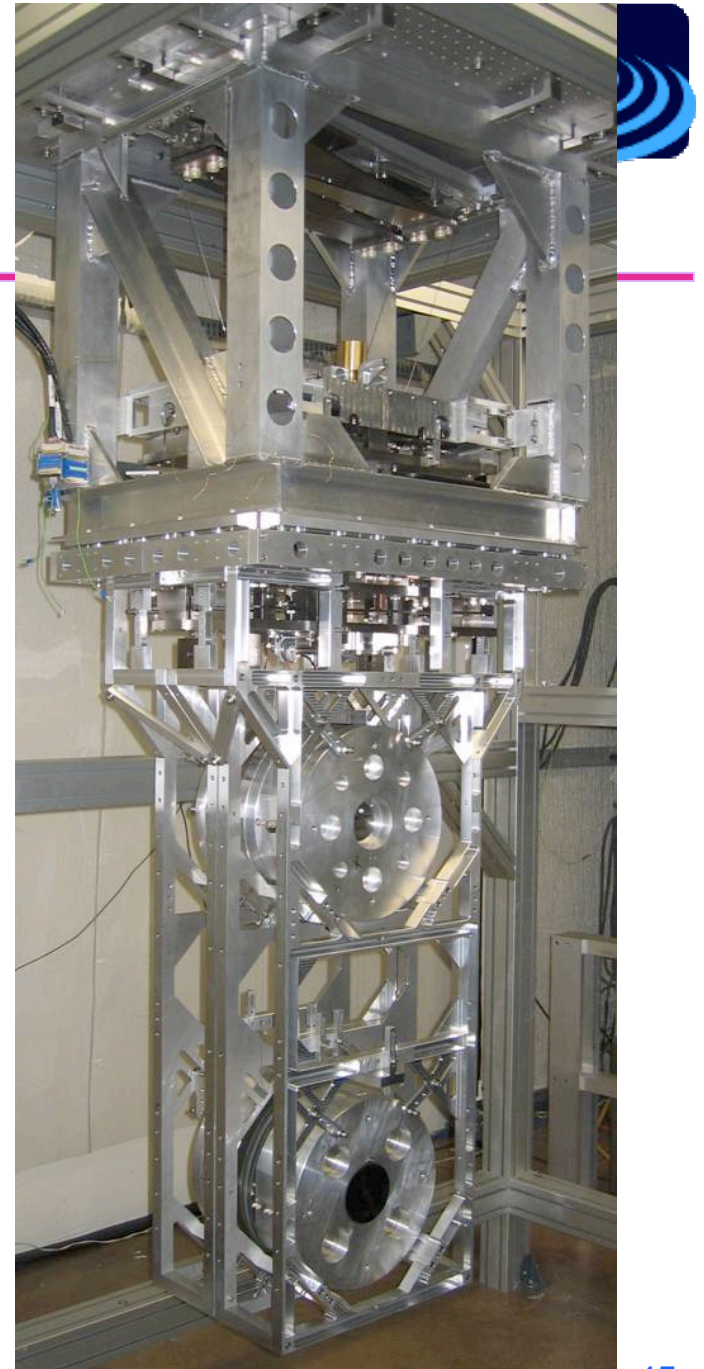


# Advanced LIGO Seismic Isolation

3 stages of active seismic isolation,  
plus 4 stages of passive isolation,  
with fused silica pendulum suspension.



*LIGO-G060291-00-Z*





## Other plans for the Advanced Interferometer era

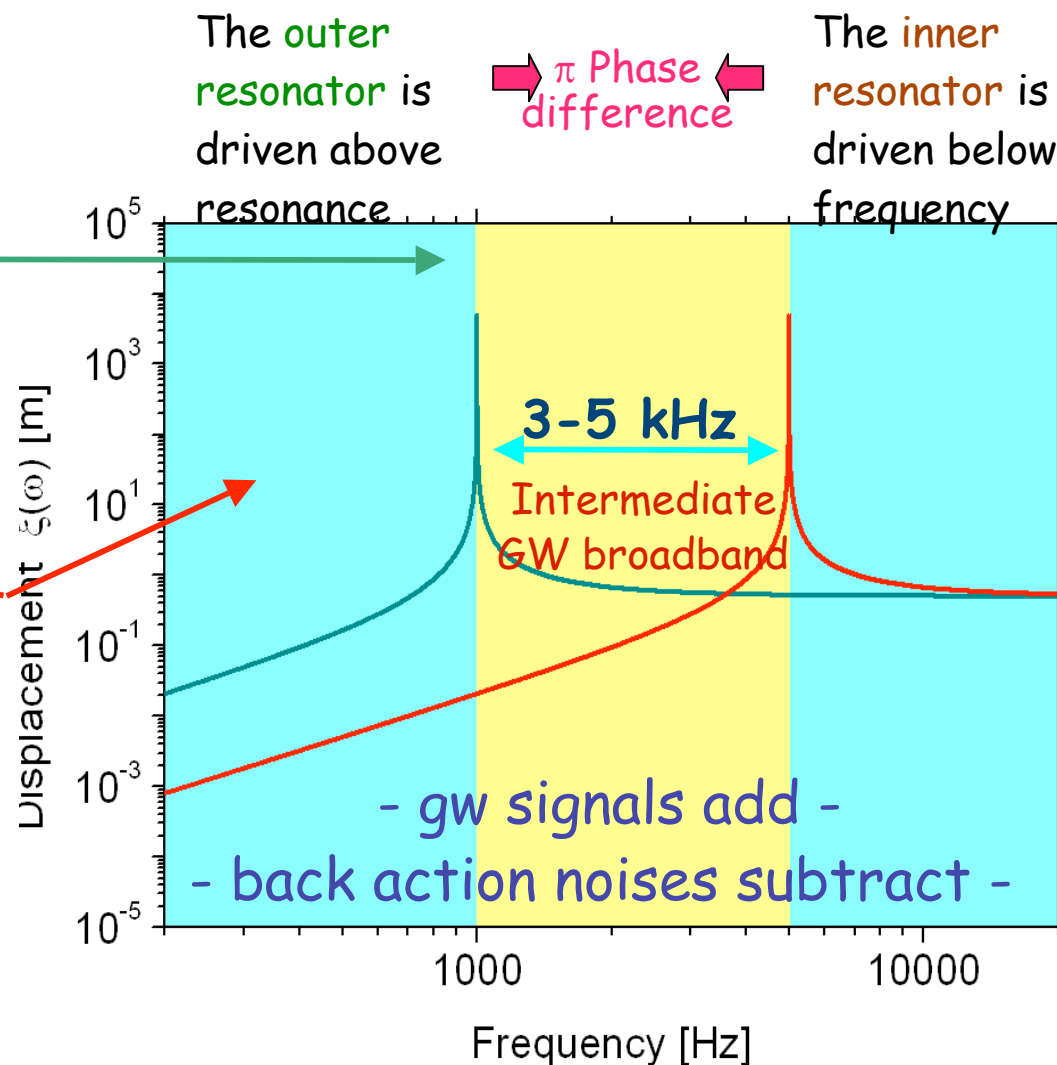
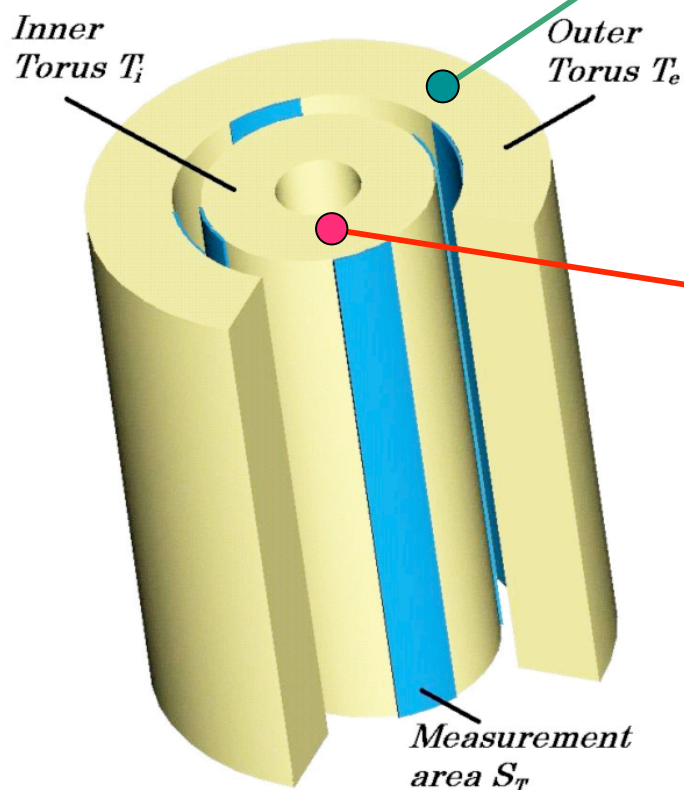
---



- Advanced Virgo will be built on the same time scale as Advanced LIGO, and will achieve comparable sensitivity.
- Japan's Large Cryogenic Gravitational Telescope (LCGT) will pioneer cryogenics and underground installation.
- GEO HF will improve the sensitivity beyond GEO 600's, mainly at high frequency where shorter length is not an issue.
- Resonant DUAL technology could equal or surpass that of interferometers at high frequencies.

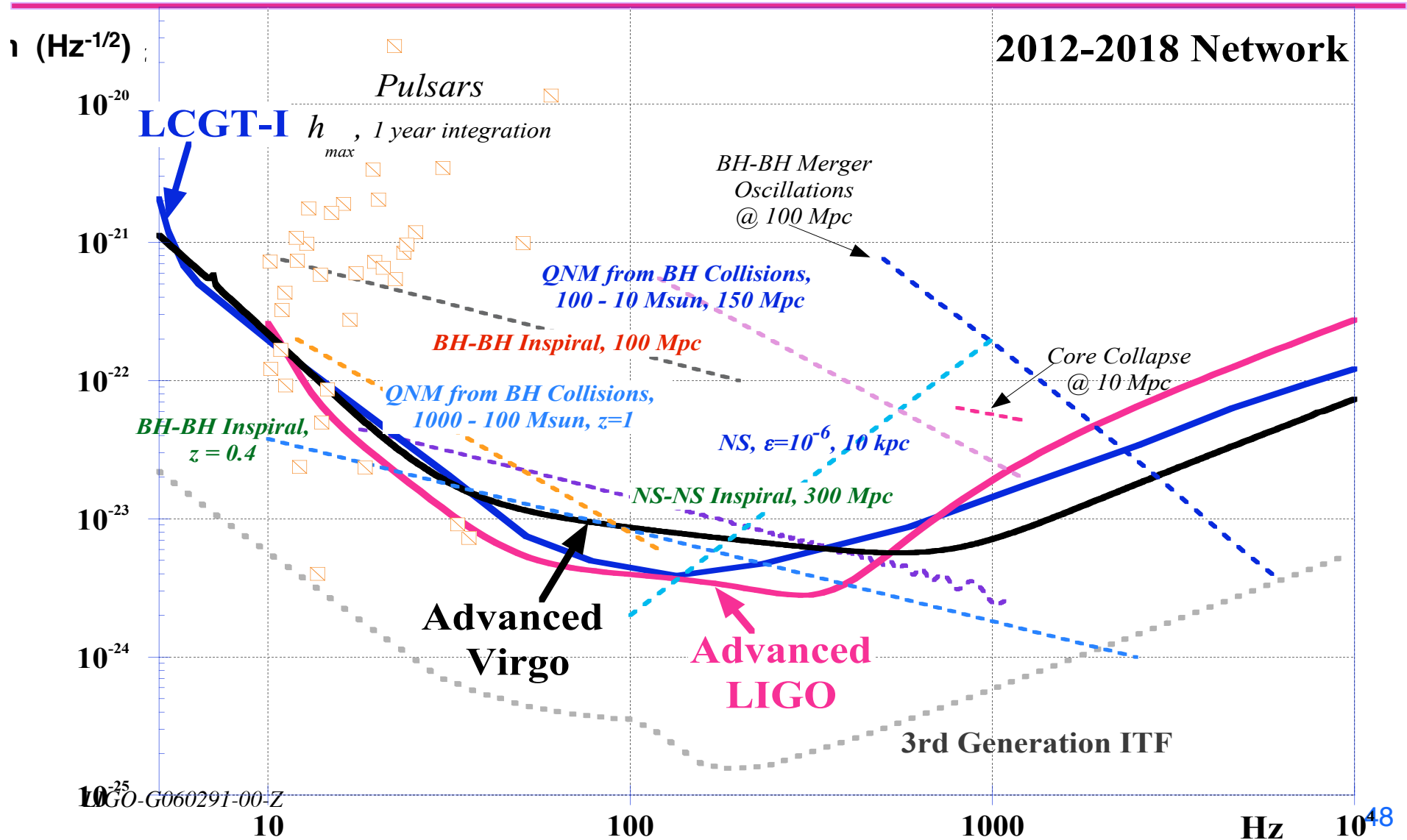
# The DUAL concept

Read the differential deformations of two nested resonators





# Advanced detectors, next decade





# Summary



---

Gravitational wave detectors on the ground are now operating full-time at unprecedented sensitivity.

Detection of gravitational waves by ground based detectors *is* expected, if not from this generation, then from its successors that will start construction within a few years.